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THESIS

BUILDING A LOCAL SPACE SITUATIONAL AWARENESS (SSA) ARCHITECTURE USING HOSTED PAYLOADS

by

Farakh B. Zaman

September 2013

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13. ABSTRACT (maximum 200 words)

From a military standpoint, space-based capabilities and the need to know what is happening in space, or Space Situational Awareness (SSA), have become invaluable. Current SSA capabilities are expensive and are limited in scope. Hosted payloads however, provide a unique method to provide SSA in a relatively inexpensive manner. This thesis explores the development of an architecture for SSA using hosted payloads.

For this thesis, research was conducted on existing systems. NASA and Air Force programs were reviewed to gain an understanding of hosted payloads, and a set of generic high-level requirements were developed for a hosted payload. These requirements will meet the needs of a hosted SSA payload that can enable a larger SSA architecture using hosted payloads. Once the requirements were developed, modeling and simulation using Satellite Tool Kit (STK) was were employed to develop an optimal SSA system using hosted payloads. Finally, once the architecture was defined, an Operational View – 1 (OV-1) was developed to provide a graphical representation of the architecture.

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BUILDING A LOCAL SPACE SITUATIONAL AWARENESS (SSA) ARCHITECTURE USING HOSTED PAYLOADS

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LIST OF ACRONYMS AND ABBREVIATIONS

AFOTEC	Air Force Test and Evaluation Center
AFSPC	Air Force Space Command
ASAT	Anti-satellite
C2	Command and Control
CDR	Critical Design Review
CHIRP	Commercially Hosted Infrared Payload
CIU	Common Interface Unit
DoD	Department of Defense
DoDAF	Department of Defense Architecture Framework
EMP	Electro-magnetic Pulse
EOIR	Electro-optical and Infrared
FAA	Federal Aviation Administration
FOM	Figure of Merit
FOV	Field of View
GBAS	Ground Based Augmentation System
GEO	Geostationary Earth Orbit
GIG	Global Information Grid
GOLD	Global-scale Observations of the Limb and Disk
GPS	Global Positioning System
HEO	Highly Elliptical Orbit
IMINT	Imagery Intelligence
IR	Infrared

IRIS	Internet Routing In Space
ISS	International Space Station
JSpOC	Joint Space Operations Center
Km	Kilometer
LEO	Low Earth Orbit
LWR	Laser Warning Receiver
m	meter
MEO	Medium Earth Orbit
MISTI	Multispectral Imaging System for the Thermosphere and Ionosphere
NASA	National Aeronautics and Space Administration
NRO	National Reconnaissance Office
OPCOM	Operational Command
OV	Operational View
OV-1	Operational View-1
PM	Program Manager
RAAN	Right Ascension of the Ascending Node
RF	Radio Frequency
RWR	Radio Warning Receiver
SASSA	Self Aware Space Situational Awareness
SSN	Space Surveillance Network
STK	Satellite Tool Kit
SWAP	Size, Weight and Power
TACOM	Tactical Command

TIGRIS	Thermosphere Ionosphere Global and Regional Imaging System
TRD	Technical Requirements Document
TRL	Technology Readiness Level
USAF	United States Air Force
USCG	United States Coast Guard
WAAS	Wide Area Augmentation System

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EXECUTIVE SUMMARY

From a military standpoint, space-based capabilities and the need to know what is happening in space, or Space Situational Awareness (SSA), have become invaluable. Current SSA capabilities are expensive and are limited in capabilities. This researcher was motivated by the possibilities that hosted payloads could provide for SSA. Hosted payloads are small payloads attached to larger satellites that typically perform missions independently of the host spacecraft. Hosted payloads afford a unique method to provide SSA in a relatively inexpensive manner. With this in mind, this thesis explored the development of architecture for SSA using hosted payloads.

For this thesis, research was conducted on existing systems. Air Force and NASA programs were reviewed to gain an understanding of hosted payloads. What was found was a sporadic use of hosted payloads to accomplish various missions. There are various government agencies that use hosted payloads for applications such as remote sensing, navigation and scientific applications. However, the use of hosted payloads with respect to SSA was limited. Additionally, there is no single standard for hosted payloads to be built to. Instead hosted payloads are custom made for each particular application. Instead of having custom-built payloads for every mission, a foundation to build hosted payloads for SSA missions was developed in the form of high-level requirements. The nine requirements laid out in Table 2 of this thesis build the foundation for hosted payloads to be used for SSA missions. Once the requirements were developed, modeling and simulation using Satellite Tool Kit (STK) was employed to develop a notional SSA system using hosted payloads.

The STK modeling was done to show the capabilities of a SSA system. Stakeholder analysis was employed to make assumptions about what a notional SSA system using hosted payloads limited to a single plane should consist of. The resulting system was a three-sensor hosted payload SSA system. The first sensor was a nadir facing (e.g., Earth facing) optical sensor for detecting ground-based threats. The other two sensors faced forward and aft to detect threats along the orbital path. The various parameters for the optical sensors such as detector pitch (e.g., pixel size), focal length and

cone angle were optimized to provide the maximum amount of SSA coverage possible in 24 hours. For the nadir sensor, this meant greater number of revisits over a single point on earth in a 24-hour period. Additionally, the orbit for the notional system was also optimized to find the best inclination, semi-major axis and right ascension of the ascending node (RAAN). Finally, once the notional system was fully modeled in STK, an architecture was defined in an Operational View – 1 (OV-1) to provide a graphical representation of the architecture.

There are areas for further research before the concepts in this thesis could be made into an operational system. However, the research and analysis conducted in this thesis provides a sound starting point for making a SSA system using hosted payloads.

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I. OVERVIEW

A. INTRODUCTION

"Well our object collision budget's a million dollars," says NASA Project Director Dan Truman in *Armageddon*. "That allows us to track about 3% of the sky, and begging your pardon sir, but it's a big-ass sky." While this quote by Truman's character in the 1998 movie isn't exactly true, as the United States space surveillance budget for 2012 is approximately $400 million dollars, the sentiment expressed by him is (Butler 2013, 1). Space is a vast expanse and the ability for mankind to track objects in space is limited. Even in the areas close to Earth, the ability of the United States to track objects is not as great as one may think (Weeden 2009, 2). In the United States Air Force, the ability to track objects in space is commonly referred as space situational awareness (SSA).

SSA today is more important than ever due to the fact that more nations are gaining the capability to place objects in space (United States Air Force 2004, 1). From the middle of the 20th century to today, the use of space has gone from being the object of science fiction, to being entwined in the daily lives of human beings. While some may not realize, the technology used in space today touches most people's daily lives in significant ways. For example, when a purchase is made at a gas station, a Global Positioning System (GPS) satellite is involved in time stamping the transaction (Stromberg 2013). Our smart phones and mapping sites such as Google Maps use imagery collected by satellites (Richelson 2008, 175). People use GPS navigation systems to know where they are in the world. Airplanes use satellite communication to receive messages from control towers. These are just a few examples of how space technology has become part of the daily lives of average citizens.

From a military standpoint, space-based capabilities and the need to know what is happening in space, or SSA, has become invaluable as well (United States Air Force 2001, 1).

> Just as the advent of airpower greatly enhanced military operations of the time, space forces, likewise, greatly enhance modern military operations across the spectrum of conflict. Space assets have not only added to our

> defense capabilities but have also changed the way our military does business. Air Force doctrine views air, space, and information as key ingredients for dominating the battlespace and ensuring superiority (United States Air Force 2001, 1).

Protecting U.S. space-based capabilities requires SSA. While the current system of SSA sensors provides data required to maintain a catalog of space objects, the capability is limited (Weeden 2009, 1). Objects of a certain size or in certain locations in space cannot be accurately identified and tracked in a timely manner (Weeden 2009, 2). At times even the objects that can be tracked have errors in their position data. For example, in February 2009, the accidental collision between two satellites took place (Weeden 2009).

> The facts known about this collision are as follows. On February 10 at 1156 EST, Iridium lost contact with one of its satellites, Iridium 33. They contacted the Joint Space Operations Center (JSpOC) at Vandenberg requesting help with resolving the anomaly. Using their network of radars, the JSpOC confirmed that there were two breakups, one corresponding to the inclination of Iridium 33 and another in a different inclination, later discovered to be that of Cosmos 2251 (Weeden 2009, 2).

The U.S. space surveillance network (SSN) was tracking these two objects, and yet they still collided (Weeden 2009, 2). This is just one example of a collision in space. There are other instances of space collisions (Weeden 2009, 3). In addition to having to worry about accidental collisions between spacecraft and debris, there are other dangers in space as well. Small debris, such as the thousands of pieces created by the Chinese antisatellite test in 2007, can pose significant risk to orbiting spacecraft (Weeden 2009, 4).

Some may ask why additional sensors are not placed around the world to track objects. The main reason is cost. Placing sensors around the world is expensive, on the order of hundreds of millions of dollars (Pearson, Levin and Oldson 2008, 2). There is also a single system in space, which provides SSA, the Space Based Space Surveillance Satellite (SBSS): however, this too is extremely expensive (Pearson, Levin and Oldson 2008, 2). The SBSS satellite launched by the USAF's Air Force Space Command (AFSPC) in 2010, cost more than $1 billion (Pearson, Levin and Oldson 2008, 2). So how does the U.S. get the SSA it needs while staying within financial realities? In this thesis, a method of changing the paradigm of how the U.S. conducts SSA collection is examined.

While there will be a continued need for ground-based radars, as well as large space-based sensors such as SBSS, a paradigm shift is needed regarding the collection of SSA. Adopting the concept of “local” SSA, and building architecture to accomplish this would better serve the SSA community. “Local” SSA expands the traditional definition of SSA to encompass an understanding of the immediate natural and manmade environment of the satellite. The way to achieve “local” SSA is by adding small payloads to larger satellites. The only mission of these small payloads would be to provide SSA. By adding these hosted payloads to larger space missions, multiple insights would be enabled. These insights include:

- Baseline trending to support anomaly identification and resolution
- Catastrophic failure investigation
- Threat detection
- Targeting detection
- Collision avoidance and failure attribution

Additionally, protection measures could potentially be enabled to ensure space asset availability; these protection measures would function similar to flares on an aircraft (Johnson and Zaman 2012, 1).

Finally, moving forward with a combination of traditional SSA and “local” SSA capabilities would allow a potential “global” SSA picture to be developed (Johnson and Zaman 2012, 1). By utilizing this combination of hosted payloads, as well as traditional methods for SSA, robust SSA can be achieved, mainly through data fusion and exploitation (Johnson and Zaman 2012, 2). The goal of this paper is to examine how a local SSA architecture can be achieved using hosted payloads.

B. BACKGROUND

Knowledge of basic terminology and principles related to space is essential for a full understanding of the discussion in this thesis. In addition, an understanding of how the U.S., and in particular the USAF, conducts space operations is also important.

Humans have utilized various areas of space around the Earth for different purposes. These areas of space are commonly referred to as orbits. The primary orbits for

satellites are low Earth orbit (LEO), medium Earth orbit (MEO), geosynchronous Earth orbit (GEO) and highly elliptical orbit (HEO) (Chatters IV, Eberhardt and Warner 2009, 89). Figure 1 from Chatters IV, Eberhardt and Warner (2009) below shows the various orbits and the missions associated with each orbital regime.

Orbit Type	*Mission*	*Altitude*	*Period*	*Tilt*[a]	*Shape*
LEO					
• Polar sun-synchronous	Remote sensing/ weather	~150–900 km	~98–104 min	~98°	circular
• Inclined nonpolar	International Space Station	~340 km	~91 min	~51.6°	circular
• Polar non–sun-synchronous	Earth observing, scientific	~450–600 km	~90–101 min	~80–94°	circular
MEO					
• Semisynchronous	Navigation, communications, space environment	~20,100 km	~12 hours	~55°	circular
GEO					
• Geosynchronous • Geostationary	Communication, early warning, nuclear detection, weather	~35,786 km	~24 hours (23h 56m 04s)	~0°	circular
HEO					
• Molniya	Communications	Varies from ~495 km to ~39,587 km	~12 hours (11h 58m)	63.4°	long ellipse

[a]Orbits roughly stay in the same plane. This indicates the tilt or inclination of this plane relative to the equator. Near zero is along the equator, and near 90° is over the poles. Greater than 90° indicates against the rotation of the earth.

Figure 1. Orbit Types (From Chatters IV, Eberhardt and Warner 2009, 90)

LEO satellites orbit the Earth at an altitude between approximately 100 and 1,000 statute miles (160 to 1,600 km). At this altitude, the time a satellite takes to orbit the earth is about 100 minutes. This orbit time is also known as a period (Chatters IV, Eberhardt and Warner 2009, 89).

The inclination of an orbit is equal to the maximum latitude the satellite reaches. The term inclined nonpolar orbit in Figure 1 refers to all LEO satellites that are not in near polar orbits. These types of orbits are used when the need to see every point on the earth (e.g., global coverage of the earth) is not necessary, as in the case of the International Space Station. A polar non–sun-synchronous orbit is similar to an inclined polar orbit except that the inclination is nearly polar (e.g., slightly less than 90^0

inclination). This type of orbit is used to maximize the coverage of the earth—every latitude will ultimately be passed over, and because of the fast period, a large part of the earth's surface will be seen each day [10]. This type of orbit is commonly used by communication, signals intelligence (SIGINT) and imagery intelligence (IMINT) satellites due to the fact that the Earth's entire surface will ultimately be overflown [10] [5]. Since the analysis and discussion in this thesis focuses solely on satellites in LEO orbit, MEO, GEO and HEO orbits will not be discussed further.

How a satellite travels in space is based on certain laws of physics. "Modern orbit types have been developed based on theories dating back centuries" [10]. There are two primary sets of laws that apply to motion in space [11]. Kepler's Laws of Planetary Motion are three laws that describe the orbit of planets around the sun and Newton's Laws of Motion, which describe the forces behind Kepler's laws [10]. Anything that is in space and orbiting some object will follow the principles laid out by these two sets of laws, and this applies to satellites, debris and natural objects [11]. While these principles will not be discussed in detail in this thesis, it is important for one to understand that motion in space follows a consistent set of rules. Debris as well as active space objects all will continue to move in their orbits and at times, there will be a collision if SSA is not available or accurate to facilitate and guide avoidance maneuvers.

As nations have progressed in their technological advancement, the LEO orbit has become extremely crowded [8]. Debris creating Events such as the Chinese ASAT test of 2007 and the accidental collision of Iridium 33 and and Cosmos 2251 have made the orbit even more crowded [2]. The graphical depictions below from Johnson and Zaman (2012) show just how crowded the LEO orbit has become in Figure 2 and Figure 3. Objects represented in the figures are those that are greater than the size of a softball. In Figure 2, the colors represent various densities of objects in a particular area, with green being the greatest density of objects and red being the least.

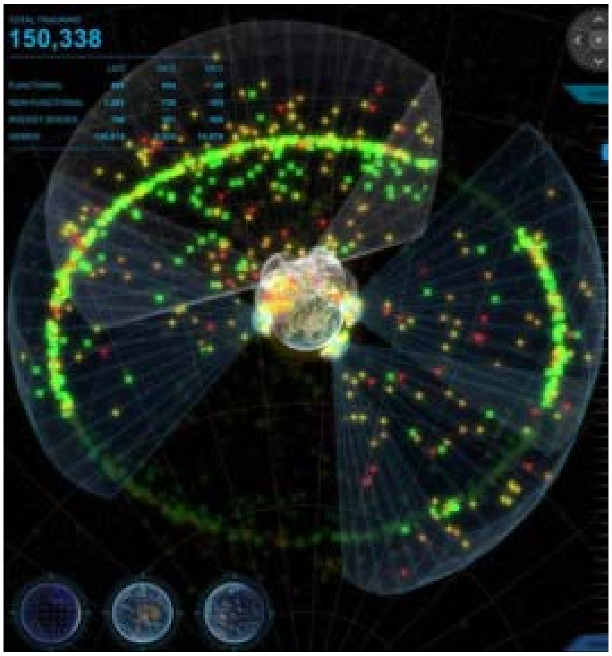

Figure 2. Satellite Tool Kit (STK) Depiction of Space Objects in LEO (From Johnson and Zaman 2012)

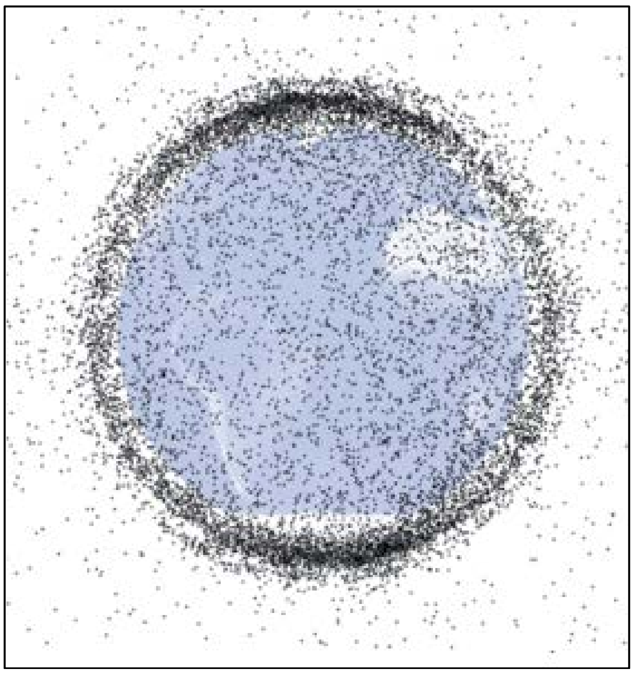

Figure 3. Artist Rendering of LEO Space Objects (From Johnson and Zaman 2012)

Satellite systems are complex systems composed of many different parts. While this discussion will primarily focus on the space segment of satellite systems, it should be understood that there are other parts as well.

> A satellite system is typically made up of one or more satellites (or space vehicles), terrestrial satellite control, and maintain elements, and user elements that permit the operational military forces to take advantage of the capabilities of the space system. Each satellite is made up of its elements, typically the payload (that provides the basic mission capability such as communications, surveillance, navigation, etc.) and the spacecraft or bus (that typically supports the payload by providing electrical power, thermal control, and attitude control, etc.). The payload and bus are, of course, subdivided into lower tier elements such as processors, sensors, communications (radios), and clocks which are in turn made up of parts (such as integrated circuits, relays, or roller bearings) and materials (such as metallic or composite structures), all fabricated and assembled using various processes.
>
> Similarly, a launch system is typically made up of the launch vehicles (which provide the initial boost toward orbit), upper or transfer orbit stages (which place the satellite in or near its operational orbit), ground control and monitoring systems, and facilities used for checking out, mating, and supporting the launch vehicles, upper stages, and satellites prior to launch. Each launch vehicle may be made up of multiple launch stages. Each launch stage and upper stage is typically made up of propulsion, guidance and control, and environmental protection elements.
>
> The distinction between launch systems and satellite systems is not always clear such as the case of the Space Shuttle which is a launch system that can also perform or support operations on orbit or the case of integral upper stages which are supplied as part of the satellite system to complete part or all of the transfer orbit function (Space and Missile Systems Center 2005, 2).

The U.S. has the capability to acquire and develop many types of space systems; however, they would not be useful without someone to operate them. United States space operations fall into several categories: defense, intelligence, space exploration and civil (Richelson 2008, 55). Department of Defense (DoD) space operations fall under the auspices of AFSPC, while intelligence space operations fall under the National Reconnaissance Office (NRO). The National Aeronautics and Space Administration (NASA) usually conducts research space operations, while civil space operations are

conducted by various businesses and can include missions such as television and communication providers. This thesis will primarily focus on DoD, or defense, operations, however, the architecture being proposed in this thesis can be applied to any or all satellite missions.

The following provides a general idea of how space operations are conducted based on this researcher's experience in the space community. For DoD operations, the Joint Space Operations Center (JSpOC) has operational command (OPCOM) over all satellite operations, and directs missions performed by various space operations squadrons (SOPs). The SOPS have tactical command (TACOM) over their respective satellites, and operate from space operations centers (SOCs). Usually each SOPs has a specific mission. For example, the fourth[t] SOPs operate the protected communications satellites or mission. The JSpOC provides direction to the fourth SOPs on various matters, such as where satellites should be positioned, users to support, or if the satellites need to be decommissioned. The fourth SOPs in turn, provide inputs to the JSPOC on how missions are progressing and if there are any issues. The SOPs generally use the ground segment, or command and control system, to control the satellites. This is a limited description of how space operations work in AFSPC but provides context for readers of this thesis.

C. PURPOSE OF STUDY: NEED FOR SSA

The economic and military might of the U.S. depends on the availability of technology in orbit. SSA is the key to protecting these vital assets. The use of space has become so important for military operations that it is now part of the basic USAF doctrine. Some key contributions of space noted in USAF doctrine are:

- "Space power bolsters U.S. global presence" (United States Air Force 2001, 1)
- "Space forces, in combination with air and information capabilities, offer ever expanding view of the globe" (United States Air Force 2001, 1)
- "Integration of space-based navigation and timing systems with airborne platforms has enhanced military precision strike capability" (United States Air Force 2001, 1)

- “Synergistically applied with other forces, space provides added flexibility in military operations” (United States Air Force 2001, 2)

SSA in particular plays a significant role in Counterspace Operations (United States Air Force 2004, 2).

> SSA is the result of sufficient knowledge about space-related conditions, constraints, capabilities, and activities—both current and planned—in, from, toward, or through space. Achieving SSA supports all levels of planners, decision makers, and operators across the spectrum of terrestrial and space operations. SSA involves characterizing, as completely as possible, the space capabilities operating within the terrestrial and space environments. SSA information enables defensive and offensive counterspace operations and forms the foundation for all space activities. It includes space surveillance, detailed reconnaissance of specific space assets, collection and processing of intelligence data on space systems, and monitoring the space environment. It also involves the use of traditional intelligence sources to provide insight into adversary space and counterspace operations (United States Air Force 2004, 2).

In addition to the above-mentioned roles of SSA, the need for SSA is amplified due to the fact that the U.S.’s space advantage has eroded over the past several decades (United States Air Force 2004, 3). “In the past, the U.S. has enjoyed space superiority through our technology development and exploitation, advanced information systems, and robust space infrastructure” (United States Air Force 2004, 3). However, today many other countries have similar capabilities thanks to “technology sharing, materiel acquisition and purchase of space services” (United States Air Force 2004, 4). Adversaries today have both symmetric and asymmetric attack capabilities (United States Air Force 2004). Methods of attack include: ground system attacks, radio frequency (RF) jamming, laser systems capable of interfering with satellites, electromagnetic pulse (EMP) weapons capable of degrading or destroying satellite and/or ground system electronics, kinetic antisatellite (ASAT) and information operation capabilities capable of corrupting space-based computer systems (United States Air Force 2004, 4). All of these threats justify the need for an ability to conduct SSA to protect U.S. space-based assets.

Furthermore, if all space capable nations continue to place assets in space, even with only peaceful intentions, the U.S. will still have a problem. There is no significant

effort for debris removal in space currently, so the risks of collisions will continue to increase as more objects occupy the same usable orbits (Johnson and Zaman 2012, 3).

D. RESEARCH QUESTIONS

As discussed previously, there is a need for SSA to protect U.S. space systems, and this need will only increase as space gets more congested. Hosted payloads offer one potential way to continue improving the U.S. SSA capability. However, just placing hosted payloads on satellites will not solve the entire SSA problem. Instead, an architecture must be developed to guide the deployment of these sensors. To gain a better understanding of how hosted payloads can be used to enhance U.S. SSA capabilities, this thesis will explore the following two questions:

1) What are the requirements for an individual satellite to provide local SSA using a hosted payload?

- Means to find answer: Perform a survey of hosted payload capabilities and develop a generic set of requirements based on this survey.

2) How should individual SSA payloads be distributed to provide a worldwide SSA picture? In other words, what should the architecture look like?

- Means to find answer: Use STK to perform a simulation of hosted payloads in a singular orbital plane. From this data, an extrapolation will be made on how a worldwide SSA picture could be provided using hosted payloads. The results will be presented in an Operational View – 1 (OV1) format.

By providing an SSA picture from the spacecraft's perspective using hosted payloads and using data fusion to provide a global SSA perspective, this thesis seeks to discover if the paradigm of SSA can be shifted from a catalog based mindset to a truly global SSA mindset (Johnson and Zaman 2012, 2). A global mindset, as related to SSA, is one that takes into account not only catalog data, but data provided by onboard sensors as well and has been fused to provide greater synergies than if the data were presented alone. By shifting to a global mindset, the U.S. will not only increase its ability to track and identify space objects; it will continue to maintain U.S. dominance in space. Maintaining U.S. dominance in space would mean the continued freedom to operate not

only in space, but also throughout the world, since space supports all aspects of U.S. operations (U.S. Strategic Command 2012, 3).

E. BENEFITS OF STUDY

This study will provide a rationale for using hosted payloads to provide SSA on DoD systems. Additionally, the simulation performed in this study will attempt to quantify how many systems would need to be deployed to provide a worldwide SSA picture using hosted payloads. Using the results of this thesis, a space program office within the DoD could develop a tailored set of requirements to put a hosted SSA payload on a satellite being acquired. Furthermore, if a program office is launching multiple satellites, the results of this thesis may be used to help determine how many hosted SSA payloads would be required to ensure an entire constellation is protected. Finally, this thesis could provide policy makers with a basis to provide funding for future acquisitions, and possibly develop a mandate to have onboard SSA capabilities on all space systems.

F. SCOPE AND METHODOLOGY

1. Scope

For this thesis, the scope of the requirements analysis and payload distribution study will be bounded to a single orbital plane in LEO. The LEO orbit was chosen due to the high number of satellites in this orbit when compared to other orbits. A single orbital plane was chosen due to the fact that the results from one orbital plane can be extrapolated and applied to other orbits if desired. However, it should be noted, there may be other considerations if multiple planes are analyzed. This could include, but is not limited to, how satellites orbiting in various planes intersect or what different sensor capabilities are needed to monitor in multiple planes.

2. Methodology

The approach for accomplishing this study involved three phases. The first phase of this study started with a survey of various hosted payload and sensor capabilities. Mostly, the research focused on hosted payload studies and programs conducted by Air Force Space Command, due to AFSPC being the focal point for space systems in the U.S.

government. However, research conducted by NASA, private industry and academia was also evaluated.

One program that got intense focus during the first phase of this research was the Self Aware Space Situational Awareness (SASSA) program. This was primarily due to the fact that the author of this thesis was the USAF Program Manager (PM) for this program. As the PM, the author of this thesis oversaw the SASSA program from Critical Design Review (CDR) through launch and operations, and has an intimate understanding of how the SASSA hosted payload requirements were developed and the capability fielded.

In the second phase, using information gleaned from Phase One, a generic set of requirements for a hosted SSA payload was developed. While this set of requirements is not all encompassing, it provides a sound basis for developing a set of requirements that can be tailored for a particular space mission.

Finally, in the third phase, the requirements developed for the hosted SSA payload were input into a STK simulation. The simulation was run to determine how many hosted SSA payloads would be required in a single orbital plane to provide a “global” SSA picture. This simulation assumed that a data fusion capability to integrate the data from the propagated payloads already existed and was not taken into account for this thesis. Once the simulation was completed, an OV-1 was developed.

II. SYSTEMS ENGINEERING METHODOLOGY

A. INTRODUCTION

As capabilities and technologies have progressed in the DoD, the practices and standards across the various aspects of systems engineering and program management have been defined as standards. These standards, set out for industry and DoD acquisition organizations, provide a standard roadmap to follow and help ensure a successful acquisition. Systems engineering will be used in this thesis to ensure the various aspects of the research questions are taken into account.

B. GENERAL SYSTEMS ENGINEERING

The area of systems engineering, in general, is rooted in two areas: program management and technical engineering (Blanchard and Fabrycky 2011, 17-18). Due to this twofold focus, systems engineering provides essential inputs to execute effective technical designs, as well as manage a program successfully (Blanchard and Fabrycky 2011, 17-18). Unlike ground systems, space systems typically only have a single chance at success. A failed launch usually means a failed system and/or mission. For this reason, in space systems acquisition, systems engineering is used in every aspect of the acquisition to ensure the system will work correctly upon launch.

The definition for systems engineering is not set in stone. Unlike the hard engineering disciplines such as electrical, civil and mechanical engineering, systems engineering is based on a more holistic foundation. Systems engineering looks at an object, or system, consisting of interrelated or interacting elements instead of focusing on a single item as the other disciplines might (Nelson 2013, 28). By surveying various descriptions of systems engineering, an adequate definition for systems engineering can be obtained. Standard definitions of systems engineering include:

> 1. An interdisciplinary approach and means to enable the realization of successful systems (International Council on Systems Engineering 2004).
>
> 2. An interdisciplinary approach encompassing the entire technical effort to evolve into and verify an integrated and life-cycle balanced set of

system people, product, and process solutions that satisfy customer needs. Systems engineering encompasses (a) the technical efforts related to the development, manufacturing, verification, deployment, operations, support, disposal of , and user training for, systems products and processes; (b) the definition and management of the system configuration (c) the translation of the system definition into work breakdown structures; and (d) development of information for management decision making (Blanchard and Fabrycky 2011, 17).

3. The application of scientific and engineering efforts to (a) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation; (b) integrate related technical parameters and ensure compatibility of all physical, functional and program interfaces in a manner that optimizes the total system definition and design; and (c) integrate reliability, maintainability, safety, survivability, human engineering, and other such factors into the total engineering effort to meet cost, schedule supportability and technical performance objectives (Kockler, et al. 1990, 16)

4. An interdisciplinary collaborative approach to derive, evolve, and verify a life-cycle balanced system solution which satisfies customer expectations and meets public acceptability (IEEE 1998, 10).

5. An approach to translate operational needs and requirements into operationally suitable blocks of systems. The approach shall consist of a top-down, iterative process of requirements analysis, functional analysis and allocations, design synthesis and verification, and systems analysis and control. Systems engineering shall permeate design, manufacturing, test and evaluation, and support of the product. Systems engineering principles shall influence the balance between performance, risk, costs, and schedule (Defense Acquisition University 2009, 2).

As one can see from the descriptions above, there are a variety of definitions for systems engineering. Some are concise, while others discuss the many facets of systems engineering. While the definitions from the various sources differ somewhat, one can also observe common themes. These commonalities include:

1. A top-down approach that views the system as a whole. Although engineering activities in the past have adequately covered the design of various system components (representing a bottom-up approach), the necessary overview and understanding of how these components effectively perform together is frequently overlooked (Blanchard and Fabrycky 2011, 18).

> 2. A life-cycle orientation that addresses all phases to include system design and development, production and/or construction, distribution, operation, maintenance and support, retirement, phase-out, and disposal. Emphasis in the past has been placed primarily on design and system acquisition activities, with little (if any) consideration given to their impact on production, operations, maintenance, support, and disposal. If one is to adequately identify risks associated with the up-front decision making process, then such decisions must be based on life-cycle considerations (Blanchard and Fabrycky 2011, 18).
>
> 3. A better and more complete effort is required regarding the initial definition of system requirements, relating these requirements to specific design criteria, and the follow-on analysis effort to ensure the effectiveness of early decision making in the design process. The true system requirements need to be well defined and specified and the traceability of these requirements from the system level downward needs to be visible. In the past, the early "frontend" analysis as applied to many new systems has been minimal. The lack of defining an early "base line" has resulted in greater individual design efforts downstream (Blanchard and Fabrycky 2011, 18)
>
> 4. An interdisciplinary team approach throughout the system design and development process to ensure that all design objectives are addressed in an effective and efficient manner. This requires a complete understanding of many different design disciplines and their interrelationships, together with the methods, techniques, and tools that can be applied to facilitate implementation of the system engineering process (Blanchard and Fabrycky 2011, 18).

In summary, systems engineering is not the same as traditional engineering disciplines. Instead it is a process that provides a well thought out and highly disciplined and rigorous approach to fielding systems. Instead of looking at one part of an acquisition, systems engineering looks at the entire life cycle and uses an interdisciplinary approach to achieve objectives.

For this thesis, a systems engineering approach will be applied to address objectives effectively and efficiently. A top down approach will be taken, to view the SSA system as a whole, rather than separate components. By utilizing this approach, an architecture can be developed to provide a "global" SSA system.

C. SPACE SYSTEMS ENGINEERING

Up to this point, systems engineering has only been discussed in general terms. Since this thesis is focused on space systems, there are some nuances about space systems engineering that must be addressed as well. The Space and Missiles Systems Center (SMC) is the USAF's acquisition organization for space systems. Since this researcher is assigned to SMC, SMC documentation was primarily used for research in this thesis. It should be noted, there are other sources to obtain space systems engineering knowledge, such as NASA, other DoD components and the Aerospace Corporation. For the purposes of this thesis, these sources were reviewed but are not discussed here. This is due to the fact that the sources reviewed provided similar guidance as the SMC guidance.

The main source used for space systems engineering was a SMC developed guide for systems engineering within the space context, the *SMC Systems Engineering Primer & Handbook*. Within this handbook, three areas are highlighted for space systems, which are different from other DoD systems. The first is "the space environment" (Space and Missile Systems Center 2005, 2).

> The space environment places additional constraints on the satellites and the components and parts that make up the system – near total vacuum, ambient thermal inputs varying from direct sun illumination in one direction to the near absolute zero of deep space in others, and passage through belts of charged particles to name three. These constraints must be characterized, and the hardware must be designed to survive and operate in space. Special test facilities such as thermal vacuum chambers are required to verify that the hardware can operate in the environment. In addition, high vibration, acoustic, shock, and other environments during launch and deployment into the operational orbit require careful characterization, design, and testing to prevent irretrievable failures during launch and early on-orbit operations.

For the system being proposed in this thesis, the space environment will be considered and accounted for in the architecture and requirements. This thesis will not go into depth on meeting specific target values for each environmental factor and will only account for them in general terms.

The second area that must be considered is a reality with space systems that doesn't usually apply to land or air based systems: this is the fact that most systems must have unattended operations, and remain in service with very limited ability to fix hardware issues (Space and Missile Systems Center 2005, 3).

> The space based elements of all military space systems developed so far operate unattended. For that reason, if a component fails, only remote maintenance actions can be carried out. Such actions must usually be preplanned and take advantage of provisions designed into the hardware such as redundant hardware or re-loadable software. As a result, satellites are usually designed to eliminate (or at least minimize) single point failures. Also, redundancy has been increasingly designed into launch systems. When the redundant hardware also fails, the satellite may no longer provide the intended capability. Therefore, high reliability parts are also used. Further, care is taken to verify that the hardware has a positive margin with respect to the launch and space environments described above. When a software defect affects operation, the satellite must usually be capable of being placed in a safe mode until the defect can be identified and corrected. Therefore, software that could cause the irretrievable loss of a mission is validated through such steps as extensive simulations, sometimes with flight hardware in the loop. Experience shows that the cost of these steps together with the cost of space launch is perhaps ten times or more the cost of comparable hardware deployed in terrestrial applications. Balancing such factors as performance, cost, and reliability is a systems engineering task for all systems, but the high cost of space equipment places an extraordinary premium on balancing the operational capability to be provided with other factors such as cost, reliability, and service life. To achieve balance, alternative approaches or concepts must be compared or traded off against each other with respect to effectiveness, affordability, and risk (Space and Missile Systems Center 2005, 3).

There is the remote possibility that astronauts could service a failed component; however, for such a scenario to arise, the benefits would have to be significant. As such a scenario is highly unlikely, it will not be considered as a possibility in this thesis. The requirements developed in this thesis will intend for the system to conform to unattended operations as described above.

The final consideration one must take into account about space systems is the fact that space is the ultimate high ground (Space and Missile Systems Center 2005, 3). Because of this, space systems are subject to a unique set of constraints due to their high costs, and desire for multiple forces—air, land and sea—to use them (Space and Missile Systems Center 2005, 3)

> Military forces have strived for the high ground for millennia because of the advantages it provides including the increased ability to observe or survey the enemy and the operational environment, maintain line of sight communications with friendly forces, and orient oneself with respect to the enemy and the surrounding terrain. Space provides the ultimate high ground so it is not surprising that current military space systems provide for surveillance of both potential enemies and the meteorological conditions in the operational theatre as well as communications and navigation. New systems are being planned or under development to extend these capabilities. But the cost to build and launch satellites means that each must be exploited to the extent practical by all land, sea, and air forces. As a result, many of the space programs are joint programs to provide capability to be used by in joint operations by elements of all the military forces. The user equipment for such systems can become deployed on a wide range of platforms and therefore rival or even exceed the cost of the satellites and launch vehicles so that the systems engineering task of balancing effectiveness and cost can be still more demanding and important. The extreme example is the Global Positioning System (GPS) that provides navigation data via user equipment carried directly by military personnel and on most of the thousands of land, naval, and air platforms operated by the Department of Defense (and also used in a wide range of civil and private applications) (Space and Missile Systems Center 2005, 3).

If a worldwide-hosted payload architecture is adopted, then there will be possibility that multiple users would benefit from the data. While the primary mission of the hosted payload would be to provide SSA, one can imagine a scenario where the data could be mined for other uses, such as by the intelligence community. As described above, the system requirements will need to account for this possibility.

Due to these three unique areas that apply to space systems engineering, tasks that are routine on most programs become increasingly difficult on space systems. The system boundary is much wider, and as such, the application of systems engineering must be all encompassing as well. In this thesis, this researcher will apply a comprehensive systems engineering process to ensure general and space specific concerns are taken into consideration.

III. PROBLEM DEFINITION

A. CURRENT CAPABILITIES

To understand the type of system that would be needed to perform a SSA mission using hosted payloads, research was conducted to determine the types of capabilities were currently in use. Current SSA architecture, hosted payloads and various sensors were reviewed. During the research, sources from within various government entities were evaluated including AFSPC and NASA. Additionally, industry and academia sources were considered.

As far as SSA architecture is concerned, AFSPC was the authoritative source for current capabilities. There is an existing SSA architecture known in the DoD as the U.S. Space Surveillance Network (SSN). The U.S. primarily leverages the SSN, a system of radar and optical ground sites positioned around the globe, to form its SSA architecture (Levin 2002). Figure 4 depicts the locations of the U.S. SSN ground sites.

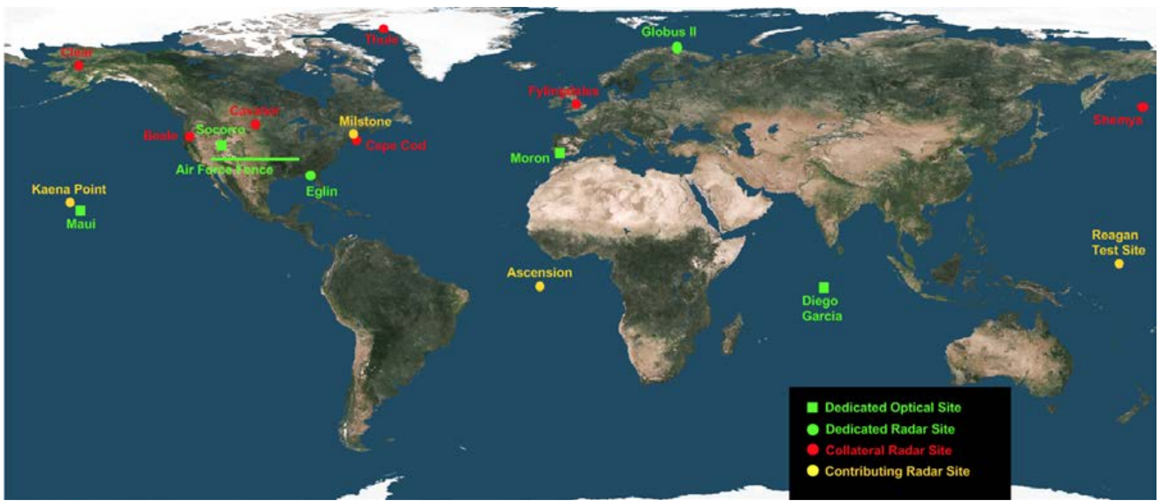

Figure 4. U.S. Space Surveillance Network (From Johnson and Zaman 2012)

The radars feed into the JSpOC, along with data collected from SBSS and other contributing sensors to form the space catalog. These items form the basic components of the U.S. SSA architecture. While this architecture provides SSA, it differs in approach from what this thesis is advocating. Additionally, the architecture discussed here has

limitations. By using primarily ground sites, there are limitations with respect to field of view, weather, over flight, range, and resolution. (Weeden 2009, 4). Field of view is limited due to the fact that a radar or optical site positioned at a particular point on Earth can only see what its aperture allows. If there is inclement weather, limitations can be introduced into the radar and optical sites. Radars can be affected by precipitation depending on their operating frequency. Optical sites are susceptible to limitations if there are clouds blocking the field of regard. When a radar or optical site is a fixed site, i.e., cannot be repositioned, then over flight limitations become a concern. The particular sites can only be useful when a satellite is flying over the particular site. Range becomes a concern depending on the altitude of a particular spacecraft. While LEO orbits are not difficult to monitor with radar and optical sites, GEO orbits are orders of magnitude more difficult to monitor, as objects can be more than 35,000 km away. Finally, resolution of images captured is a concern with ground sites. Since the resolution on grounds sites is limited by the radar aperture or focal plane of the optic, there are times objects can be not detected or are mischaracterized (Weeden 2009, 4-7).

With respect to hosted payloads, there were two government organizations perusing hosted payloads in a continuing manner, NASA and the USAF. Additionally, there are other government organizations that have already utilized hosted payloads on a limited basis. The organizations that have used hosted payloads on a limited basis include the Federal Aviation Administration (FAA), U.S. Coast Guard (USCG) and DoD. These payloads were hosted on satellites to support various missions and supported this thesis's assertion that cost savings are achievable by using hosted payloads (Andraschko, Antol and Baize, et al. 2012, 2).

The FAA system was the Wide Area Augmentation System (WAAS). WAAS was developed to provide extremely accurate navigation for civil aviation from space in conjunction with GPS satellites. Originally, the FAA had utilized a Ground Based Augmentation System (GBAS). However, similar to the on ground sites on the SSN, there were limitations in coverage in the national air space using ground-based assets. Due to these limitations, the FAA began developing hosted payloads to be flown on GEO based satellites, which would alleviate the limitations of GBAS. These payloads were

hosted on three commercial satellites: Inmarsat-4 F3, Telesat's Anik F1R and Intelsat's Galaxy 15. Instead of having to develop independent satellites at great costs, the FAA was able to utilize available space on commercial satellites to pursue their mission. The hosted payloads have been a success for the FAA and currently provide navigation continuously while maintaining the strictest safety standards (Federal Aviation Adminstration 2010, 1). Figure 5 depicts the WAAS system graphically and Figure 6 depicts the current footprints for the three hosted payloads.

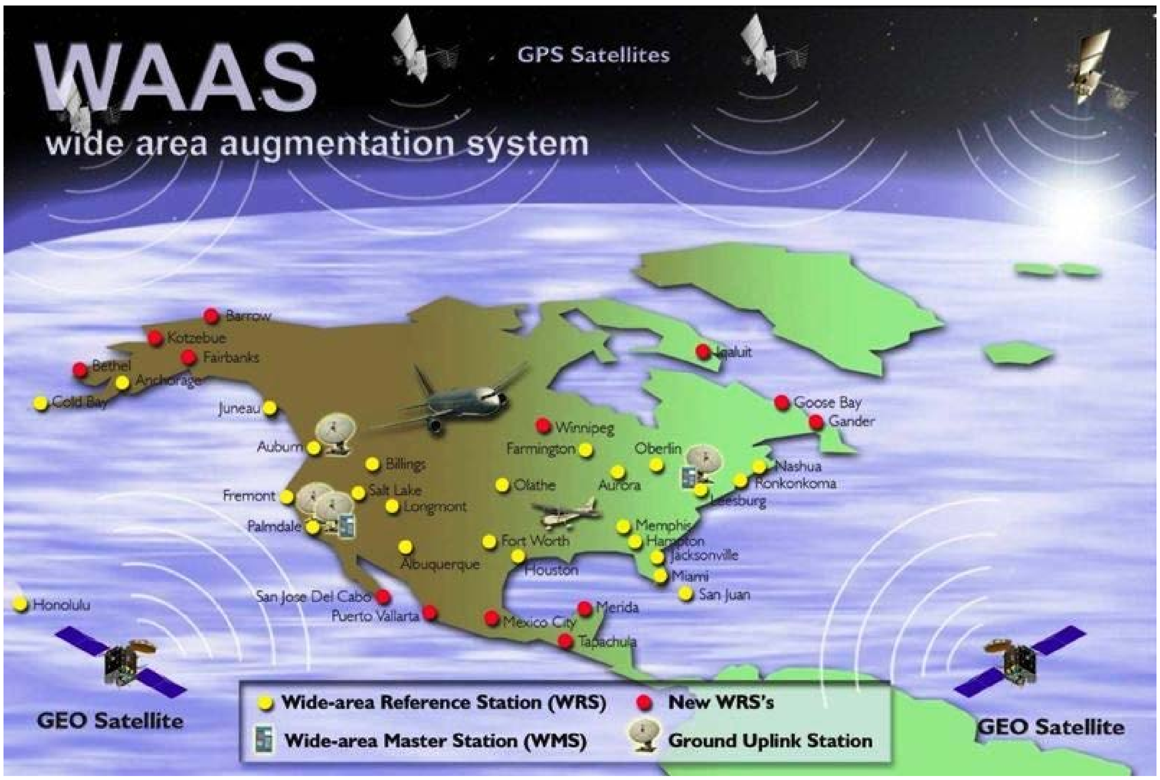

Figure 5. Wide Area Augmentation System (From Federal Aviation Adminstration 2010)

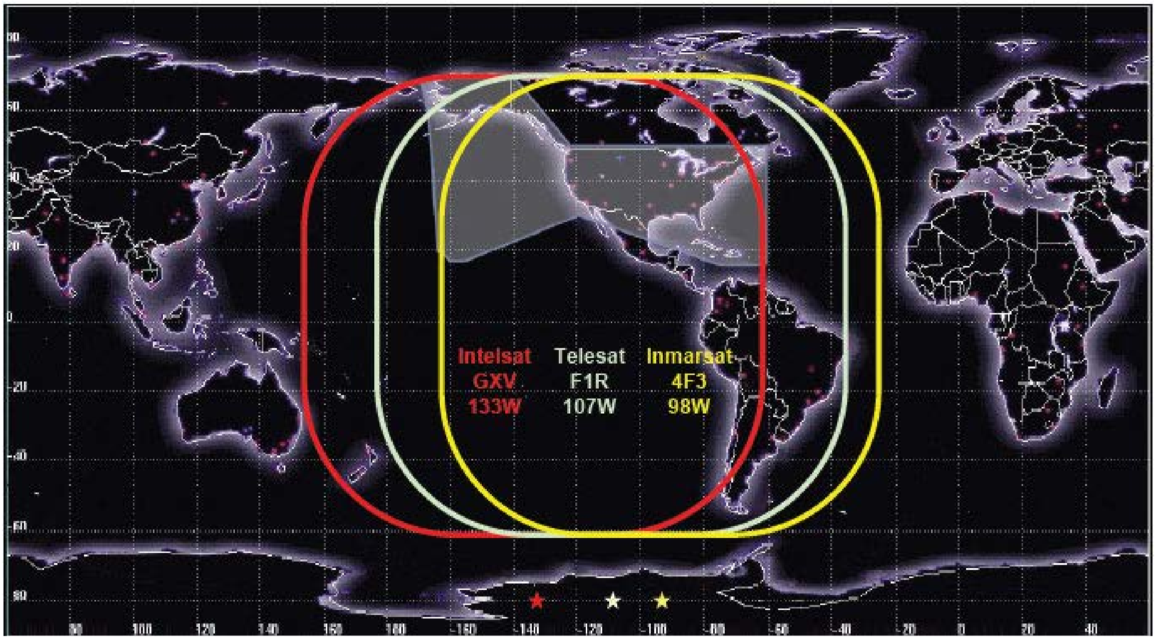

Figure 6. WAAS Footprint (From Federal Aviation Adminstration 2010)

The USCG's Nationwide Automatic Identification System (NAIS) is another example of a low cost solution to a potentially high cost problem. The USCG needed a system to monitor data from maritime traffic, including vessel location, source and speed. Ship-based transponders typically can only transmit about 46 miles horizontally. However, vertically these same transponders have reached the international space station orbiting around 400 km. By utilizing space based hosted payloads on spacecraft such as the International Space Station (ISS), ORBCOMM and Luxspace's RUBIN-9.1, the USCG avoided having to deploy costly land based systems along the entire coastline, and increased the usable range of the transponders. Additionally, by utilizing space-based systems, the USCG was able to form a comprehensive view of traffic on the nation's waterways; this better prepares decision makers in case there is an emergency (United States Coast Guard 2013, 1).

The Department of Defense, in conjunction with Cisco Systems, built a hosted payload to demonstrate Internet Routing in Space (IRIS). IRIS was a radiation tolerant IP router created as a hosted payload and launched on Intelsat-14 in GEO. Again, a hosted payload was employed to demonstrate a technology. While this payload did not provide SSA, it was able to accomplish a mission separate from the primary host. Additionally,

the reduced timeline of the hosted payload enabled Cisco and DoD to take advantage of the commercial satellite's design, development and launch cycle. Figure 7 shows a picture of the small IRIS payload developed (INTELSAT General Corporation 2013).

Figure 7. IRIS Payload (From INTELSAT General Corporation 2013)

Until 2010, NASA had yet to utilize hosted payloads in a significant way (Andraschko, Antol and Horan, et al. 2011, 2). However, in late 2010, NASA started exploring the possibilities of using hosted payloads. This was primarily due to the fact that hosted payloads offer multiple benefits for government payloads. Benefits include: lower costs, frequent launch opportunities, and leveraging of existing infrastructure. The lower costs were a significant contributor for NASA to pursue hosted payloads, due to diminishing budgets. For NASA's approach, the target hosts for hosting payloads were commercial satellites. This is mainly due to the flexibility offered with commercial providers and the steady launch cycles (Andraschko, Antol and Baize, et al. 2012, 1). Commercial programs are not subject to election cycle politics or congressional budgeting actions, which can change government launch schedules at any time. Commercial spacecraft providers see benefits from hosted payloads as well. A major benefit is the financial advantage a government customer brings to the picture. Typically commercial providers receive steady funding from government customers due to laws in place such as the Anti-deficiency Act (U.S. Government Accountability Office 2006).

A major sign hosted payloads are making inroads within NASA is the release in August 2010 of NASA’s Hosted Payload Guidebook (Futron Corporation 2010). Within the guidebook, NASA had devised a step-by-step process for developing hosted payloads. The areas covered in the guidebook are:

- Purpose/Rationale for the Guidebook
- Technical Issues
- Contractual Issues
- Payload Integration and Pre-Launch Activities
- Launch and On-Orbit Testing
- Operational Phase and End of Life Activities

The depth and breadth discussed in the guidebook provides a one-stop shop for hosted payload development within NASA and is a promising sign that hosted payloads will gain significant traction within the NASA community (Futron Corporation 2010, 3).

A further sign that NASA is marching down the path of utilizing more hosted payloads is the number of hosted payloads being built. Currently NASA has several unclassified hosted payloads in development and preparing for launch. The first is the $55 million Global-scale Observations of the Limb and Disk (GOLD), which is scheduled to launch on a SES Government Solutions commercial satellite. “Gold will fly an ultraviolet imaging spectrograph on a geostationary satellite to measure densities and temperatures in the Earth’s thermosphere and ionosphere” (U.S. Depepartment of Commerece 2013, 1). Another NASA-hosted payload being developed is the Multispectral Imaging System for the Thermosphere and Ionosphere (MISTI). This payload is to be launched on an Intelsat commercial satellite. Finally, the Thermosphere Ionosphere Global and Regional Imaging System (TIGRIS) is also being developed for launch on an Intelsat commercial satellite (U.S. Depepartment of Commerece 2013, 2).

The Air Force, on the other hand, started discussions of using hosted payloads in late 2007 with the requirements being released for the SASSA program. Previous to this instance, there had been other hosted payloads attempted; however, SASSA was the first concentrated effort to develop a standardized hosted payload which could be fielded on multiple host satellites. This hosted payload was meant to be tailorable to any desired

mission and could be fielded to do a number of tasks. The primary vision for SASSA had been a SSA payload. SASSA included a common interface unit (CIU), which allowed for various instruments to be plugged into it. SASSA's original plan called for a single technology demonstration system to be developed, tested and launched. After a successful technology demonstration, the SASSA system was to be further refined; its size, weight and power (SWAP) reduced, and fielded across all U.S. satellites. However, due to changing budget conditions within the U.S. government, only the technology demonstration was fielded. The remainder of the SASSA plan was shelved for the foreseeable future, and no production systems have been built to date. The single system fielded, however, did do a tremendous job in advancing SSA capabilities. The system launched had SSA sensors integrated and a ground system was fielded as well. The integration process onto the host spacecraft was noted in SMC as being one of the smoothest integrations ever; which is hard to come by when one is dealing with space systems (Johnson and Zaman 2012, 2-7). Another indication that the USAF wanted to pursue hosted payloads was the transfer of data and lessons learned from the SASSA program office to the Hosted Payload Office at SMC. At the time of this thesis being written, this author has first-hand knowledge that the Hosted Payload Office is continuing development of various hosted payloads and is considering the lessons learned from SASSA for future development efforts.

At the same time as SASSA was being fielded, another program by the name of CHIRP, Commercially Hosted Infrared Payload, was also being developed by the USAF at SMC. While CHIRP was not intended to be a SSA payload, i.e., it was an infrared (IR) payload, it was still developed as a hosted payload. CHIRP was successful in demonstrating that a military payload could be hosted on a commercial satellite. CHIRP's success contributed to the creation of the Hosted Payload Office in the Development Planning Directorate at SMC. The Hosted Payload Office helps push the USAF's drive to develop less expensive and more quickly field options for space missions (Simonds and Sullivan 2010, 3).

Finally, on the subject of sensors that can provide SSA, much of the specific data found was sensitive and not available to be published due to security restrictions. However, in general there are several SSA sensors that can be used. These include:

- Radar warning receivers (RWR)
- Laser warning receivers (LWR)
- Environmental sensors
- Proximity sensors
- Imaging sensors

All of these instruments can be fielded as a hosted payload or integrated into a package (e.g. SASSA's methodology). For the purposes of this thesis, generic capabilities will be used in the analysis and presented later in this thesis. No specific sensor's attributes were leveraged to perform the payload propagation simulation and architecture study.

B. STAKEHOLDER ANALYSIS

A stakeholder analysis was conducted as part of this thesis. Because space is a domain that is utilized by almost everyone, with or without their knowledge, there are a multitude of stakeholders. Table 1 lists the major stakeholders derived from the analysis. Additionally, the major stakeholders were divided into three sectors: government, private and public. The criteria used for a major stakeholder was the stakeholder would derive a direct benefit from hosted SSA payloads. Examples of direct benefits include saving an ailing spacecraft, receiving a contract to build a payload, continued use of a space asset or intelligence benefits. Minor stakeholders, such as subcontractors that may make minor parts on a SSA payload, were not included in the list.

Table 1. List of Stakeholders

ID	Stakeholder	Sector
1	Department of Defense	Government
2	NASA	Government
(Continued on next page)		

ID	Stakeholder (Continued from previous page)	Sector
3	U.S. Air Force	Government
4	U.S. Navy	Government
5	U.S. Army	Government
6	U.S. Marines	Government
7	Air Force Space Command	Government
8	Naval Space Command	Government
9	Army Space and Missile Defense Command	Government
10	Missile Defense Agency	Government
11	National Reconnaissance Office	Government
12	Central Intelligence Agency	Government
13	Defense Intelligence Agency	Government
14	National Air Space Intelligence Center	Government
15	National Security Agency	Government
16	National Geospatial-Intelligence Agency	Government
17	Air Force Research Lab	Government
18	Space & Missile Systems Center	Government
19	Space Superiority Systems Directorate	Government
20	Launch Systems Directorate	Government
21	Military Satellite Communications Systems Directorate	Government
22	Global Positioning Systems Directorate	Government
(Continued on next page)		

ID	Stakeholder (Continued from previous page)	Sector
23	Infrared Space Systems Directorate	Government
24	Space Development and Test Directorate	Government
25	Defense Weather Systems Directorate	Government
26	Spacelift Range and Network Systems Division	Government
27	Lockheed Martin	Private
28	The Boeing Company	Private
29	Northrop Grumman Corporation	Private
30	Raytheon Company	Private
31	General Dynamics Corporation	Private
32	Analytical Graphics Inc. (AGI)	Private
33	Assurance Technology Corporation	Private
34	Orbital Corporation	Private
35	Other defense contractors	Private
36	GPS Users	Public/Private/Gov
37	SATCOM Users	Public/Private/Gov
38	Television Users	Public/Private/Gov
39	Television stations	Private
40	Direct TV	Private
41	Dish Network	Private
42	SiriusXM Satellite Radio	Private
43	Satellite Radio Users	Public
(Continued on next page)		

ID	Stakeholder (Continued from previous page)	Sector
44	Foreign Allied Governments	Government
45	Joint Space Operations Center	Government
46	U.S. Strategic Command	Government
47	United Launch Alliance	Private
48	Congress	Government
49	Air Force Operational Test & Evaluation Center (AFOTEC)	Government
50	U.S. Coast Guard	Government
51	Federal Aviation Administration	Government

The stakeholders listed in Table 1 represent the majority of groups that would be involved with or benefit from a hosted SSA payload architecture. Some of the stakeholders mentioned, such as Congress or the U.S. Air Force, have direct impact on funding to a potential program and thus are included as stakeholders. The various directorates, defense contractors and launch organizations mentioned would be the primary means of fielding the architecture. Others, such as AFOTEC, may contribute to the testing and operationalization of the system. The users mentioned may not ever know that there is an SSA system in orbit assuring the continued use of various services. However, these users would benefit from the availability of systems derived from SSA. Finally, as with any sensor which produces data, there is potential intelligence that can be gathered. The intelligence organizations are included as stakeholders due to the large potential for intelligence to be derived from SSA data collected.

C. FUNCTIONAL ANALYSIS

To develop architecture for a hosted payload to perform an SSA mission, there are certain requirements the system must meet to be effective. For this thesis, research was conducted on existing systems. NASA, as well as Air Force programs, were reviewed to

gain an understanding of hosted payloads, and a set of generic high level requirements were developed for a hosted payload. These requirements will meet the needs of a hosted SSA payload that can enable a larger SSA architecture using hosted payloads. While not included in this thesis, an area of further study includes the decomposition of the high level requirements into lower level requirements and captured as technical requirements. In acquisition circles, this table would be known as a technical requirements document (TRD).

Typically, functional analysis is first employed to assist in performing concept trades and is often a major systems engineering activity. Additionally, Functional analysis is used to help yield descriptions of actions rather than a parts list (Space and Missile Systems Center 2005, 244). To begin developing requirements, a high level functional analysis was conducted as shown in Figure 8.

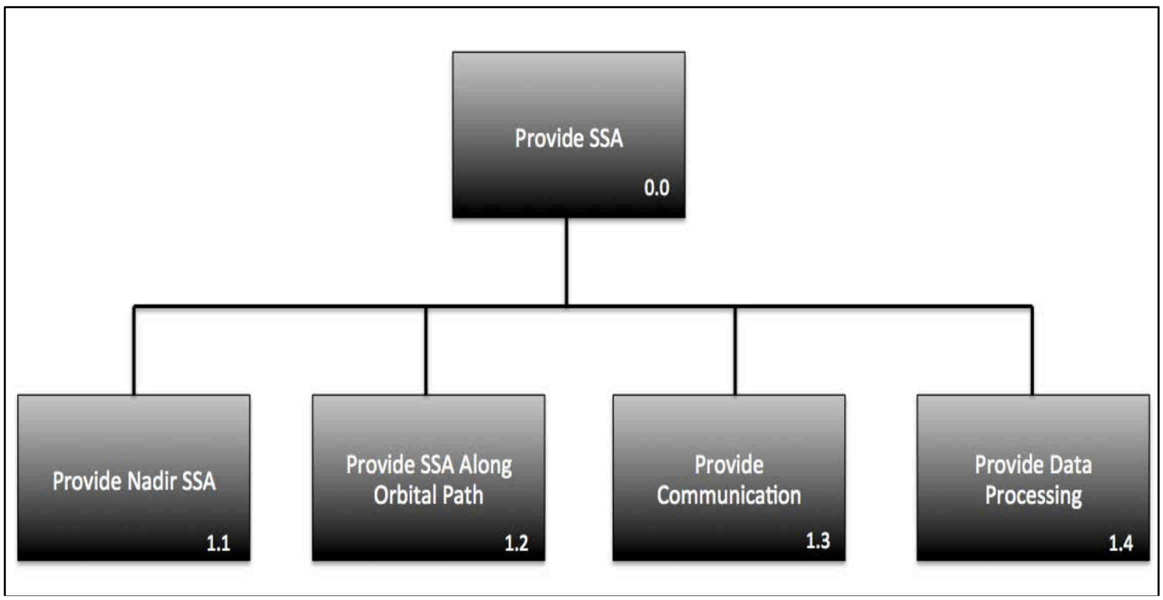

Figure 8. Functional Decomposition

The top level function, Function 0.0, is simply stated as “Provide SSA.” This top level function was then decomposed into four lower level functions, Functions 1.1 – 1.4. These four lower level functions provide the basis for the requirements development as well as the STK analysis conducted later on in this thesis.

Function 1.1 provides for SSA in the nadir, or Earth facing, direction. The function is critical to provide SSA against threats from the ground such as ground launched ASAT's, space object surveillance and identification sites, and general earth imaging.

Function 1.2 provides for SSA along the orbital path. Having SSA along the orbital path fulfills a large concern for satellite operators, knowing if there is something along the orbital path. This function will allow for collision avoidance as well as detection of space based ASAT's.

Function 1.3 provides for communication with the system. Having a SSA system on a satellite is not useful if the system is unable to communicate with the operators as well as receive commands from the operators.

Finally, Function 1.4 provides a means to process collected data and provide it to potential users. Without this functionality, the data may exist, however, there would be no method to utilize the data.

Due to the academic nature of this project as well as the availability of data from the SASSA program, further functional analysis was not performed for this thesis. However, if a program office were designing this system for operational purposes, versus an academic discussion, then a much more in-depth functional analysis would need to be included while developing requirements.

D. REQUIREMENTS ANALYSIS

To develop the high level requirements, the program level requirements from the SASSA program were leveraged and modified into the generic high level requirements listed in Table 2. Some of the requirements developed were functional requirements while others were requirements aimed at meeting various stakeholder needs. Functional requirements are shows with a (F) next to them. The requirements are coined as "generic" due to the fact that they have not been adapted to any particular mission and are meant to be a one size fits all solution. In reality, the requirements presented in Table 2 would need to be reviewed, modified or possibly eliminated depending on the needs of the actual mission. For this thesis however, the SASSA requirements were the best example of requirements found during the research, and were chosen due to the close alignment with the goals of this thesis. The high

level requirements set provides the first step of building a SSA architecture using hosted payloads by providing the foundation for the payloads themselves.

Table 2. Generic Hosted Payload Requirements

Generic Hosted Payload Requirements		
R1.0		HP **SHALL** interface with multiple common spacecraft busses - Use industry standard/common interfaces for electrical, hardware and data
R2.0		HP **SHALL** accept integration of multiple dissimilar instruments - Use industry standard/common interfaces for electrical, hardware and data
R3.0		HP **SHALL** use a modular and scalable software architecture
R4.0	(F)	HP **SHALL** use high TRL threat warning instruments - Proximity sensor, radar warning receiver (RWR), laser warning receiver (LWR), environmental sensor, camera, laser range finder, etc.
R5.0		HP **SHALL** output all sensor information in an machine and human readable format
R6.0		HP **SHALL** meet USAF launch vehicle specifications
R7.0		HP **SHALL** not interfere with host vehicle payload/bus operations
R8.0	(F)	HP **SHALL** be capable of accepting command and control (C2) inputs independent of host vehicle
R9.0	(F)	HP **SHALL** have a ground segment application that can be integrated into the host ground segment

The requirements presented in Table 2 provide a high level requirement set that can be leveraged by a government program office to provide to industry to build a material solution. Rationale for each requirement is provided in the following paragraphs.

Requirement 1.0 - HP **SHALL** interface with multiple common spacecraft busses - provides assurance that the architecture design of the payload is expandable, scalable

and supportable. By taking advantage of multiple interfaces and using industry standards, the architecture is assured to remain open. Interfaces could include RS422, 1553, space wire or Ethernet connections (Wertz and Larson 1991, 175). Using these interfaces facilitate the easy adoption across multiple spacecraft. Additionally, this requirement is important because it will allow the "global" SSA discussed earlier in the thesis to be achievable. Without the capability to adapt to varying spacecraft, the hosted SSA payload would not be able to be used on multiple spacecraft. By not fulfilling this requirement, the entire architecture would be negated. To verify this requirement, inspection would be used to ensure that the common interfaces exist on the system.

Requirement 2.0 - HP **SHALL** accept integration of multiple dissimilar instruments **–** is one of the major facilitators for a "global" SSA system. By providing the means for multiple dissimilar instruments to be integrated onto the hosted payload system, the architecture for a hosted payload SSA will be usable in various orbits against varying threats. The actual number of dissimilar instruments would depend on the type of SSA desired, and could range from two instruments to as many as the system was designed to support. In other words, if a potential host is more concerned with collisions than with the threat of being illuminated by lasers, then a proximity-sensing instrument could be used. If however the potential host was an optical imaging satellite, laser threats may be a real danger and require laser-sensing instruments. The main point of this requirement is to let the hosted payload be instrument agnostic and customizable to provide SSA against the many threats in space. Verification of this requirement would be by inspection and test. Visual inspection would determine how many instruments had been physically integrated onto the system. Testing would verify the instruments actually work once integrated.

Requirement 3.0 - HP **SHALL** use a modular and scalable software architecture **–** ensures the software architecture is modular and tailorable. "Software architecture is the set of design decisions which, if made incorrectly, may cause your project to be cancelled" (Bass, Clements and Kazman 2012, 25). For this reason, it is imperative the software architecture is designed properly. Modular software helps eliminate the need for complete software redesign in case there is a change later on in the life cycle. Modular

software is a software design technique that separates various parts of the software into individual modules. These modules are combined to form the larger software application. By using modules, if a software change is required, specific modules may be changed versus changing the entire software application. Tailorable software architecture allows various instruments to be supported as mission requirements change (Bass, Clements and Kazman 2012, 45). Verification of this requirement consists of inspection as well as test. A software expert could ensure the software is modular by inspection, in the form of a code review. Testing would be required to ensure the software can be modified and the software would continue to perform as designed.

Requirement 4.0 - HP **SHALL** use high TRL threat warning instruments – ensures that the instruments being used on the hosted SSA payload are at a high enough technology readiness level (TRL) to support operational missions. This would mean that the instruments would be at TRL 8 or TRL 9 (Space and Missile Systems Center 2005, 261). The intent of this requirement is to ensure the instruments being integrated into the system are mature, provide low risk and reliable SSA to the host spacecraft. Additionally, this requirement fulfills Function 1.1 and Function 1.2. By providing the high TRL instruments, the two directional SSA functions can be fulfilled. Verification of this requirement would need to be performed by inspection and test. Engineers could inspect documentation to ensure the TRL of the instrument has met the level of testing required. Additionally, tests could be performed on the instruments in operationally realistic environments to ensure the instruments meet the TRL.

Requirement 5.0 - HP **SHALL** output all sensor information in an machine and human readable format – is levied to ensure that once the data is processed on board the hosted SSA payload, the data is output in a standard format. The format must be machine and human readable; an example of this format would be XML. This will ensure the data is net ready and usable by multiple users. The use of propriety formats would not be acceptable to fulfill this requirement. The output format must be an open standard. Verification for the requirement would be performed by inspection and test. An engineer could inspect the output to ensure the data is human readable, while testing could be used to verify the data is machine readable.

Requirement 6.0 - HP **SHALL** meet USAF launch vehicle specifications – ensures that when the hosted SSA payload is designed and fielded, it can be launched on a United States launch vehicle. An example of a U.S. launch vehicle would be the Evolved Expendable Launch Vehicle (EELV). The reference for vehicle specifications is the EELV Standard Interface Specification Version 6.0, dated 5 September 2000. (EELV Standard Interface Working Group 2000). Verification for this requirement would be performed by simulation. A simulation of the system would need to be completed to ensure the payload is able to launch on a USAF launch vehicle using launch modeling software.

Requirement 7.0 - HP **SHALL** not interfere with host vehicle payload/bus operations – safeguards the vehicle and payloads on the host spacecraft that are not part of the hosted SSA payload. Ensuring the SSA payload works on a non-interference basis will help adoption of the hosted payload, as well as ensure other critical missions are not disrupted. Simulation and testing would be used to verify this requirement. Simulations would give the first verification that the system does not interfere with the host vehicle operations. Once the hosted payload was integrated onto the host spacecraft, additional testing would need to be performed to verify the system performs as designed and causes no interference.

Requirement 8.0 - HP **SHALL** be capable of accepting command and control (C2) inputs independent of host vehicle – allows for the hosted payload to be commanded and controlled in the case that the host command and control (C2) path is not available. Additionally, having an independent C2 path will provide redundancy and increase the reliability of the system. Furthermore, this requirement fulfills Functions 1.3 and 1.4. By providing C2 inputs, the communication and data processing functions are enabled. For this requirement, simulation and testing would be required for verification. Simulations would provide the first level of verification that the system has the ability to be independently commanded. Once the hosted payload was integrated onto the host spacecraft, additional testing would need to be performed to verify the system performs as designed. Lastly, for this requirement, there would need to be additional testing once the system was launched to verify the requirement was met.

Finally, Requirement 9.0 - HP **SHALL** have a ground segment application that can be integrated into the host ground segment – provides for the ground segment of the hosted payload to work on the existing host ground segment. This will reduce the overall footprint of the system, provide a seamless user experience, and reduce the need for multiple ground systems to be fielded. Additionally, as an application the hosted payload ground segment could be accessed by any node, versus having a dedicated node. In other words, existing computers could be utilized as the ground system instead of having to field separate stand-alone systems. Furthermore, this requirement fulfills Functions 1.3 and 1.4 by providing a means for operators to communicate with the system and receive processed data. This requirement could be verified by inspection. An engineer could verify the ground segment software was resident on the existing host ground segment visually.

The generic requirements developed here are the basis of developing a SSA architecture utilizing hosted payloads, and will be utilized in the next part of this thesis. The next step for this thesis will be to conduct modeling and simulation using STK to determine how payloads should be distributed to provide worldwide SSA coverage. In reality, if one desired to pursue developing a system based on the generic requirements presented, the requirements would need to be broken down into the detailed technical requirements before pursuing modeling and simulation. However, since only notional sensor values will be used in the simulation, further breakdown of the requirements were not necessary for this thesis.

IV. SYSTEMS ARCHITECTURE DESIGN

A. ARCHITECTURAL DEVELOPMENT OVERVIEW

A two-step was approach taken to develop the SSA architecture utilizing hosted payloads. The first step involved developing the functions and requirements for a hosted SSA payload, which serves as the basis of the architecture. The second step involved conducting analysis via simulations in STK to determine how a notional hosted payloads system would be fielded. Ultimately, the simulations provided the basis for developing the final OV-1 architecture product.

To develop a simulation to fulfill the functions and requirements, the system modeled in STK included the following items and assumptions:

- Interface/processing unit to integrate sensors onto a spacecraft
  - This interface was assumed available and no additional modeling was required
- One nadir facing optical sensor
  - For this sensor, it was assumed that the maximum Earth coverage and resolution was desired
  - Modeling was conducted to fulfill these assumptions
- Two optical sensors along the orbital path, facing forward and aft
  - For these sensors, it was assumed that the sensors would be detecting debris along the orbital path
  - Modeling was conducted to fulfill this assumption

These item and assumptions were chosen as a notional system that would be used on a LEO satellite. While other sensors or types of systems could have been used, it was determined this type of system would fulfill needs of most of stakeholders. This is due to the fact that most of the stakeholders would be concerned with collision avoidance as well as intelligence gathering. Having the assumed system provides these two aspects for

the stakeholders in a single hosted SSA system, and meets the functions laid out in Figure 8. Additionally, the proposed system provides a sufficient model to develop the OV-1.

Optimal parameters were found for the three notional sensors. Additionally, modeling was conducted to determine how many payloads would be required to cover SSA over an entire orbital plane. The analysis was conducted in STK with the understanding that the sensors were notional and not representative on any one particular sensor available currently. However, since only a single orbital plane was being analyzed, the various parameters of the constellation were optimized to ensure SSA could be maximized even in a single plane. Finally, once these two steps were completed, conclusions about the architecture were made and an Operational View – 1 (OV-1) was developed.

To conduct the STK analysis, some other assumptions were needed to facilitate the analysis and limit computational time of the software. Firstly, the hosted payload could be placed on board any notional spacecraft orbiting in LEO. Next, it was assumed the main threats to the satellite would be from the following sources: 1) ground based threats such as space object surveillance and identification (SOSI) radar and optical sites, 2) ground based laser or direct assent anti-satellite (ASAT) weapons, 3) objects along the velocity vector (i.e., path of orbit) such as debris or another satellite 4) object approaching from behind in the orbit (e.g., co-orbital ASATs). Additionally, objects considered threats will be at least 1 meter in diameter. Using these assumptions, the analysis was conducted in STK.

B. STK ANALYSIS

STK is a physics-based software package developed by Analytical Graphics, Inc. It is widely used in the space systems development to allow engineers and scientists to perform complex analysis of space assets. For this thesis, the following modules were used to conduct the analysis and would be required to recreate any of the analysis discussed:

- Coverage Module
- Electro-Optical Infrared Module
- Analyzer Module
- Optimizer Module
- Professional Module

The next portion of this thesis walks the reader through a step by step process on how optimal values for the architecture were found using STK. Using a top-down methodology, STK was used to develop the notional three-sensor hosted payload SSA system. First, STK was used to determine the optimal orbit placement for the SSA satellite constellation to provide the greatest coverage of the Earth as possible. This was done so that a single plane of satellites with nadir (e.g. Earth facing) sensors could monitor the maximum amount of ground space object surveillance and identification sites. Optimal parameters for the satellite's orbit included altitude, inclination and right ascension of the ascending node (RAAN).

For the sensors, the first sensor modeled provides nadir-facing coverage, while the second and third sensors provide SSA along the orbital path, forward and aft (e.g., backwards). For the purposes of this thesis, all three sensors were optical sensors. These were chosen due to the modeling capability in STK as well as security purposes. Modeling SIGINT sensors, such as an RWR, requires higher levels of security, thus were not modeled. Since the three sensors being modeled are optical sensors, STK was used to determine optimal focal lengths, pixel pitch (size) and resolution of the sensors. These parameters are the main characteristics of an optical system.

Finally, once the satellite and sensor's parameters were all calculated to optimal values, STK was used to populate a constellation with identical satellites in a single plane to determine how many satellites are required to provide coverage around the entire globe in a single plane.

The following list provides a summary of what was done in STK:

- An LEO orbit satellite was created
- A GEO orbit relay satellite was created to send data down to a selected point on earth; in this case Monterey, CA
- A nadir or earthward facing sensor was created
- Optimum parameters for the nadir sensor were calculated by starting at a broad range and narrowing the parameters down to the optimal value using multi-step simulations
    - Parameters for the nadir sensor include focal length, pixel pitch (size) and resolution
- Once sensor parameters for the nadir sensor were created, the forward and aft facing sensor parameters were analyzed in a similar fashion

- Parameters for the forward and aft sensors include focal length, pixel pitch and resolution

- Once sensor parameter calculations were completed, the number of satellites required to provide global coverage in a single plane was determined.

Screen shots are provided for each major step to demonstrate what process or menu was used, or to show what the output for a certain process was in order to allow others to recreate the results.

To start the analysis, an orbit was specified in STK. For the case of this thesis, a notional LEO orbit was selected as seen in Figure 9. Monterey, CA was selected as the notional ground site, and a notional relay satellite was created to pass data from LEO orbit to the ground station. In STK, the user has to specify an area of interest. The areas of interest are the points on the earth that a satellite must monitor. In other words, the locations the nadir facing sensor will monitor. In the case of this thesis, the area of interest was based on the location of land mass and commercial shipping routes. It was assumed that monitoring the polar regions was a lower priority since the analysis being done is for the optimal plane.

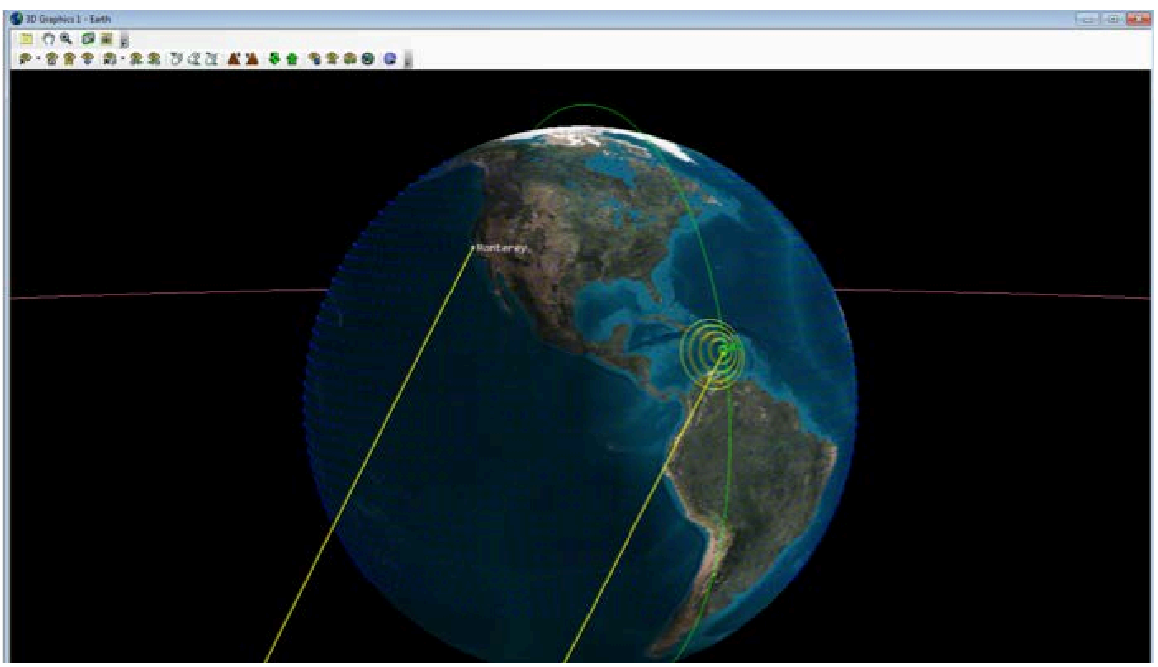

Figure 9. Selection of LEO Orbit in STK

Once the orbit was selected, the star background was removed to minimize processing needed as shown in Figure 10. To do this, the 3D Graphics window is opened and the Show in the Celestial option is deselected. This is mainly done to minimize processing time for the simulations. If desired, the celestial background can be reintroduced at a later point in time.

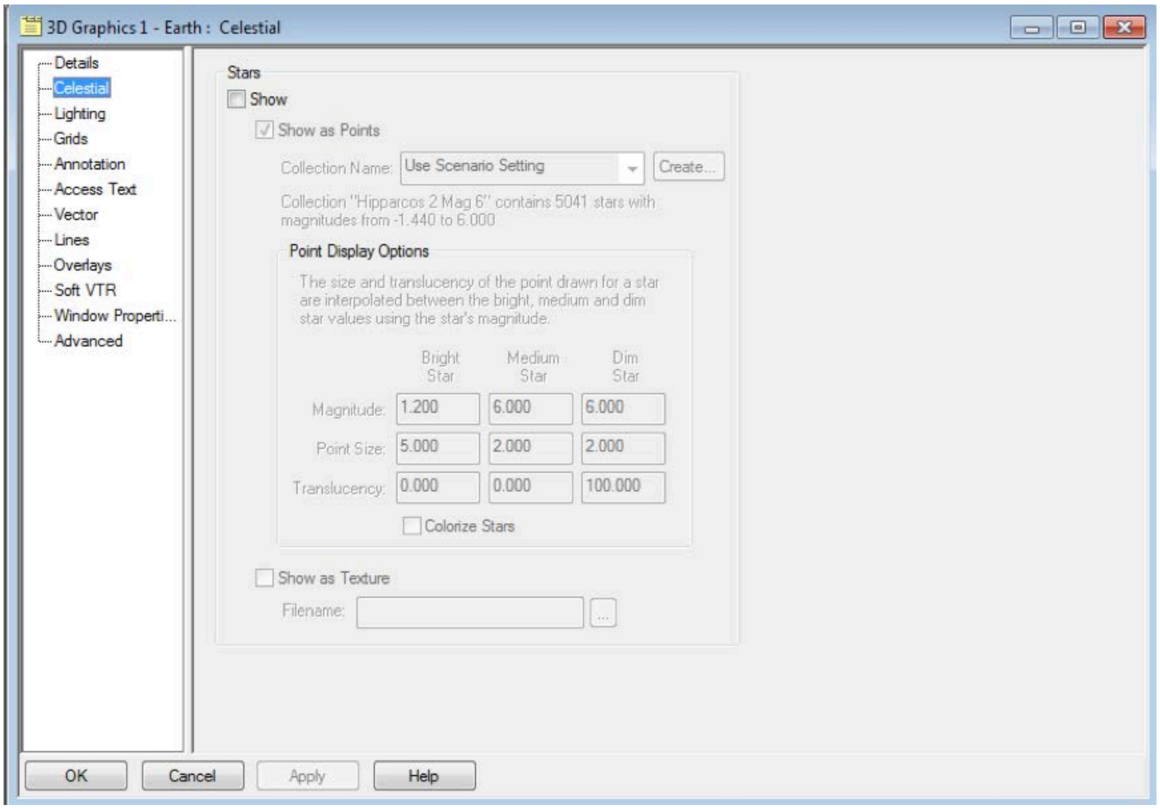

Figure 10. Remove Star Background in STK

After removing the star background in STK, the various components that have been created must be linked together so they will work together in the simulation. In this case, the linked components include a satellite with sensors in LEO orbit, a communication relay satellite in GEO orbit and a ground station in Monterey, CA. In order to create the linking, a Chain must be created by simply moving Available Objects to the Assigned list. The sequence of the list will determine the success of the Chain. Once the Chain is created, the user run the Access function in STK to finalize the Chain, and allows relaying back to Monterey. This step is shown in Figure 11.

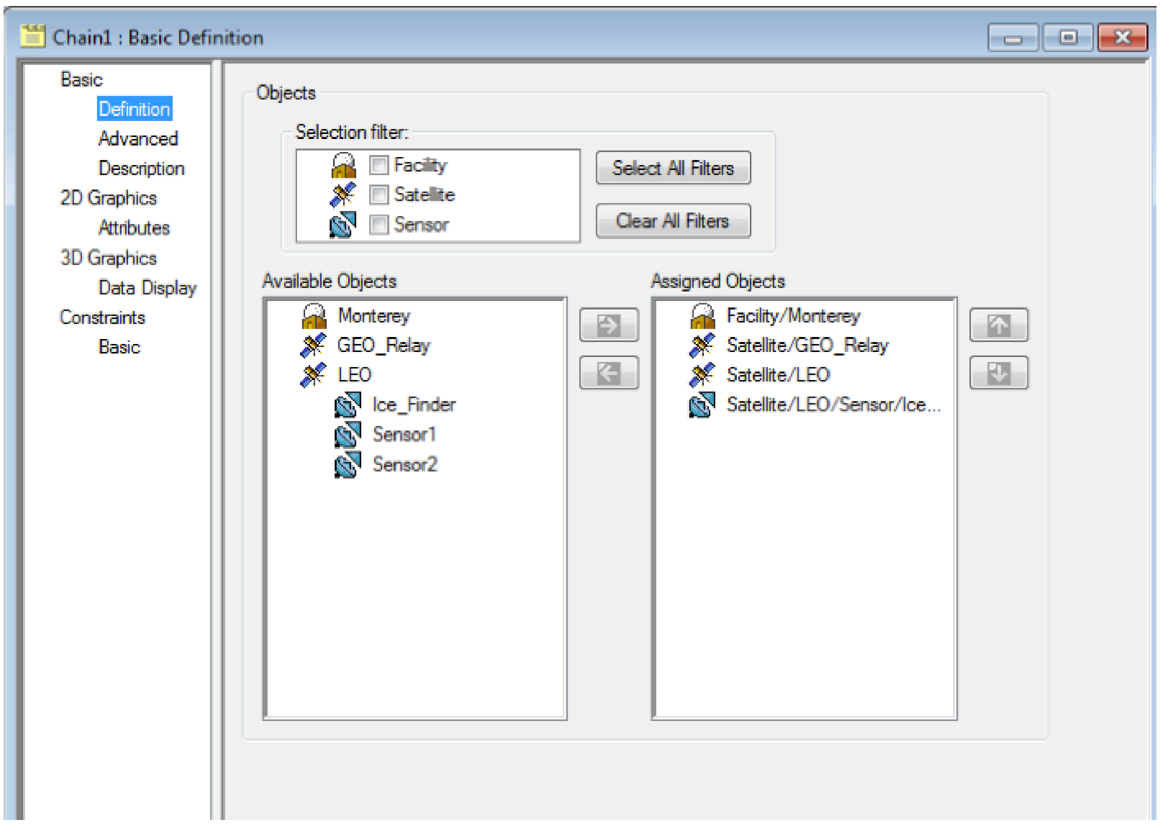

Figure 11. Creation of Chain in STK

Once the star background had been removed and a chain created, a coverage area was defined as depicted in Figure 12. Defining the coverage area takes the area of interest a step further by giving the user a visual representation of where the nadir sensor will be able to see. Additionally, the coverage area is represented in various colors, which represent how many times a particular area will be revisited in a 24-hour orbit by a single satellite. This step requires the use of the Coverage module. For this thesis, the Coverage is defined by creating the Grid Region of Interest, and the latitude is bounded from -38^0 to 62^0. These latitudes were selected since most land mass and shipping lanes lie within them (Wertz and Larson 1991, 213). Additionally, for STK, Point Granularity must be defined in this step. This is due to the fact that as the points converge during the simulation, the model fidelity increases, and so does simulation time. For this thesis, 3^0 granularity was selected since the nadir sensor will have a large field of view (FOV), and keeps the simulation times to a reasonable length. Note: if the sensor had a smaller FOV, one would decrease granularity accordingly to avoid significant miscalculation.

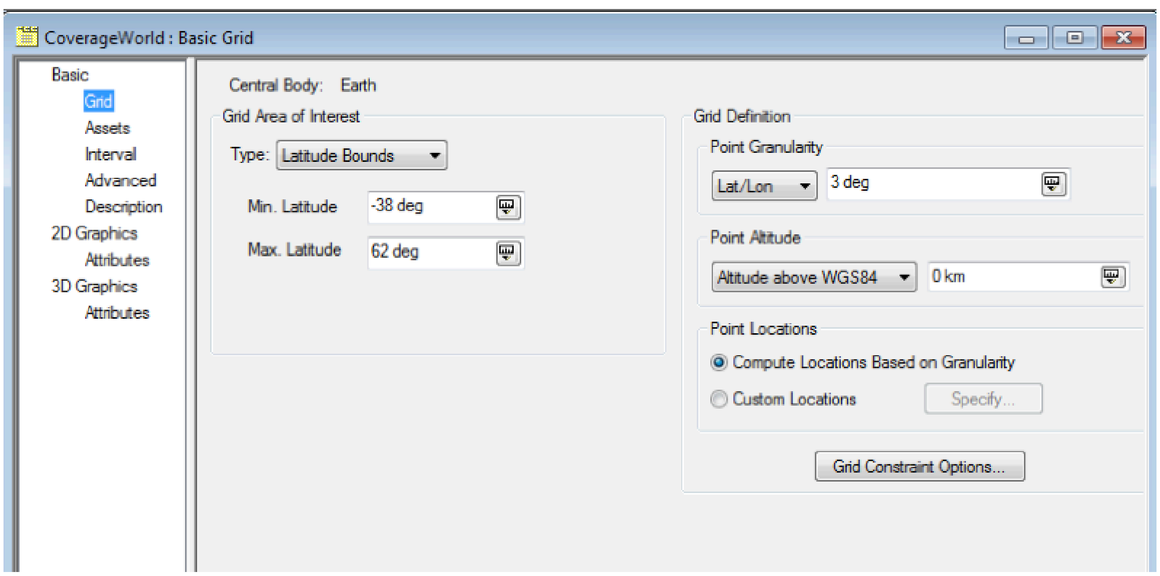

Figure 12. Define Coverage Area

After defining the coverage area, the nadir facing sensor was assigned to the system as shown in Figure 13.

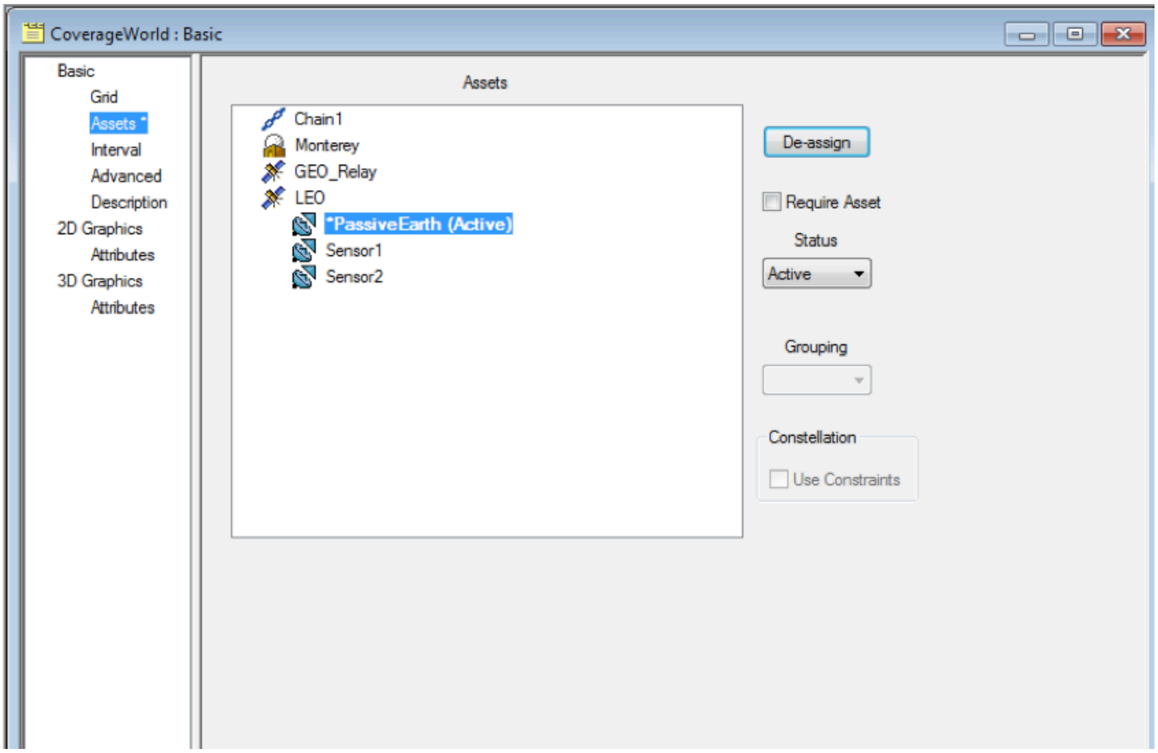

Figure 13. Assign Sensor

Once the sensors were assigned, a figure of merit (FOM) was defined as shown in Figure 14. A FOM lets the user define what type of coverage is desired from the sensor. Since this thesis is trying to provide sensor coverage to certain points on the Earth between latitudes, the FOM type was defined to be Number of Accesses.

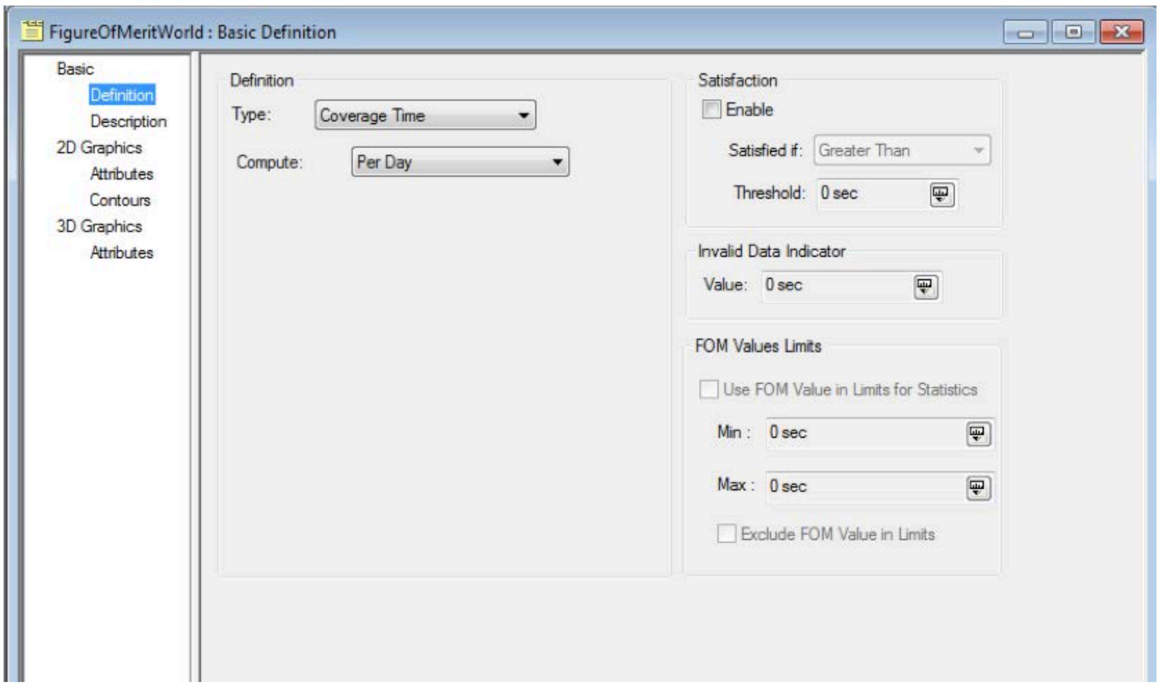

Figure 14. Define Figure of Merit (FOM)

After defining the FOM, the coverage was computed by selecting the menu shown in Figure 15. This was the first actual simulation run in STK, and the computation took approximately five minutes to execute. The computation was to determine the various orbits in which the notional satellite could be placed and how many revisits were possible by a single satellite.

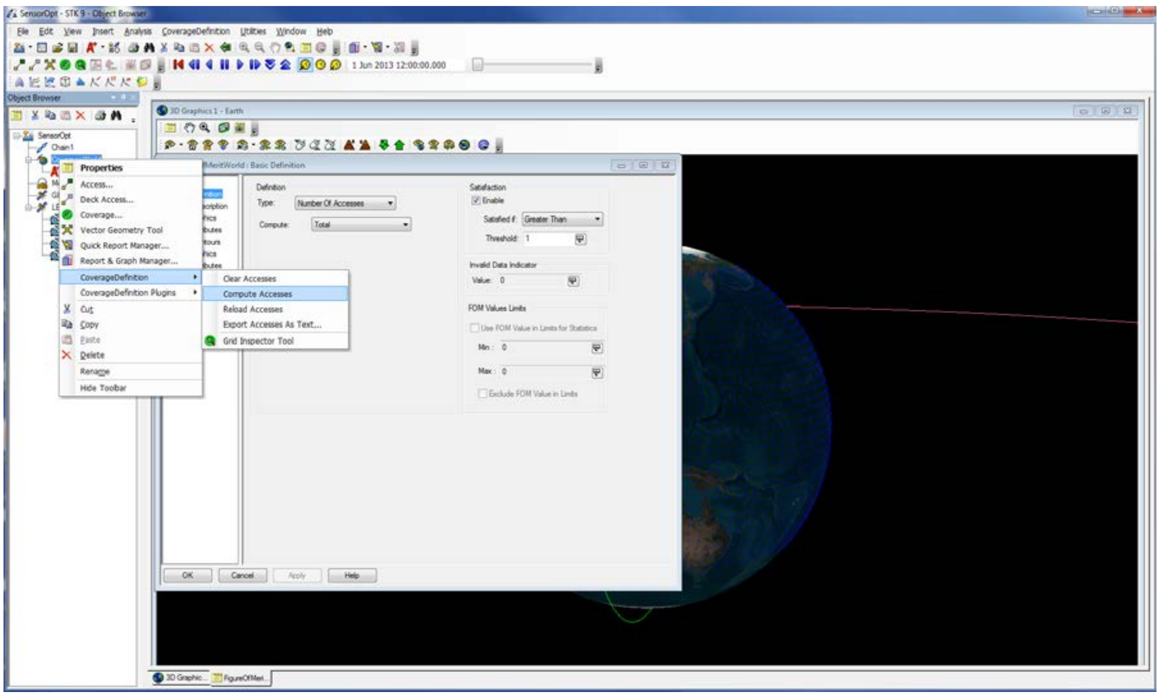

Figure 15. Run Coverage

After running coverage, a legend was made as shown in Figure 16. This was done to provide a key to differentiate what each color represents on the globe in Figure 17.

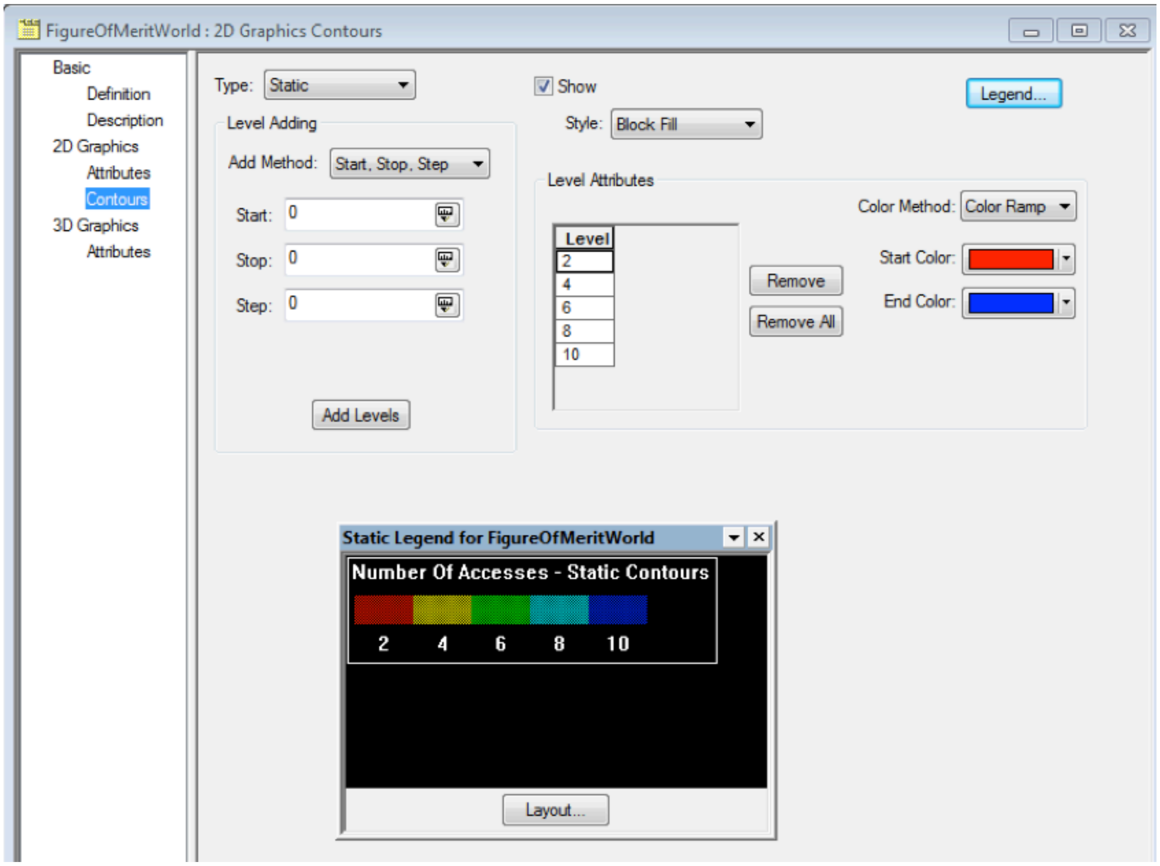

Figure 16. Legend

Once the legend was made, the coverage was completed as shown in Figure 17. The coverage shown represents the areas the Nadir facing sensor will be able to see while in the orbital plane and number of revisits to the particular site in a 24 hour period.

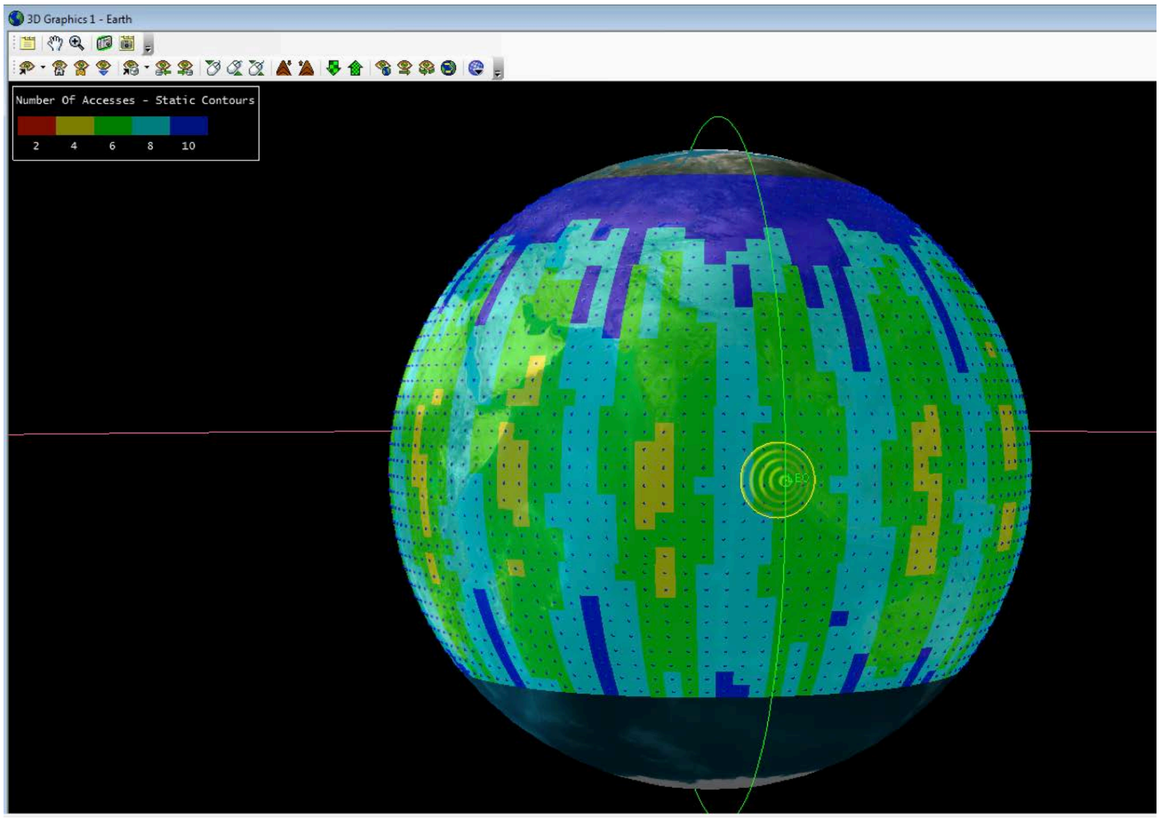

Figure 17. Completed Coverage

Once the coverage simulation was completed, the next step was to exploit the analyzer module to determine an ideal orbit for the SSA mission using hosted payloads. The setup of this is shown in Figure 18.

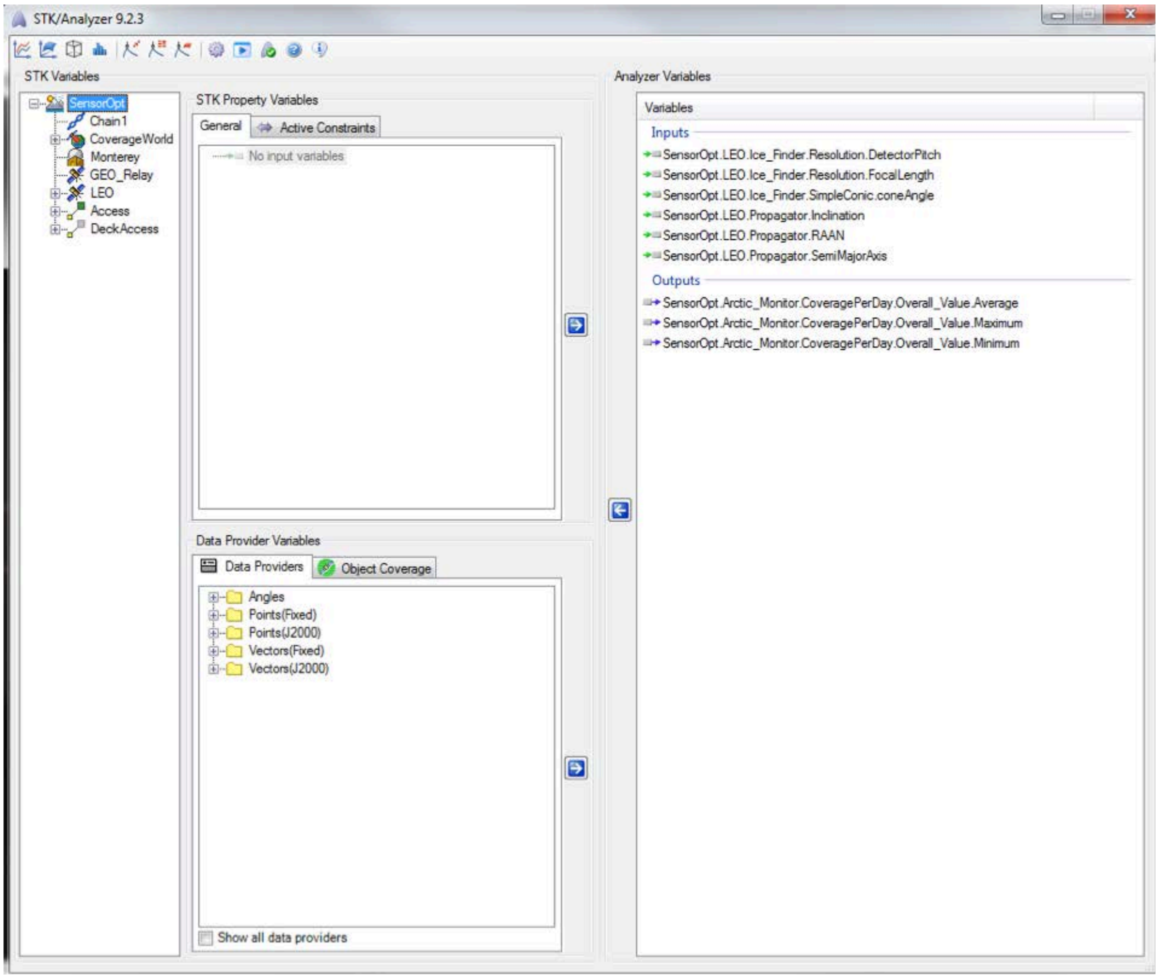

Figure 18. Analyzer Setup

Once the analyzer was configured in general, the Parametric Study Tool is used to first determine what optimal inclination of the orbit would be as shown in Figure 19.

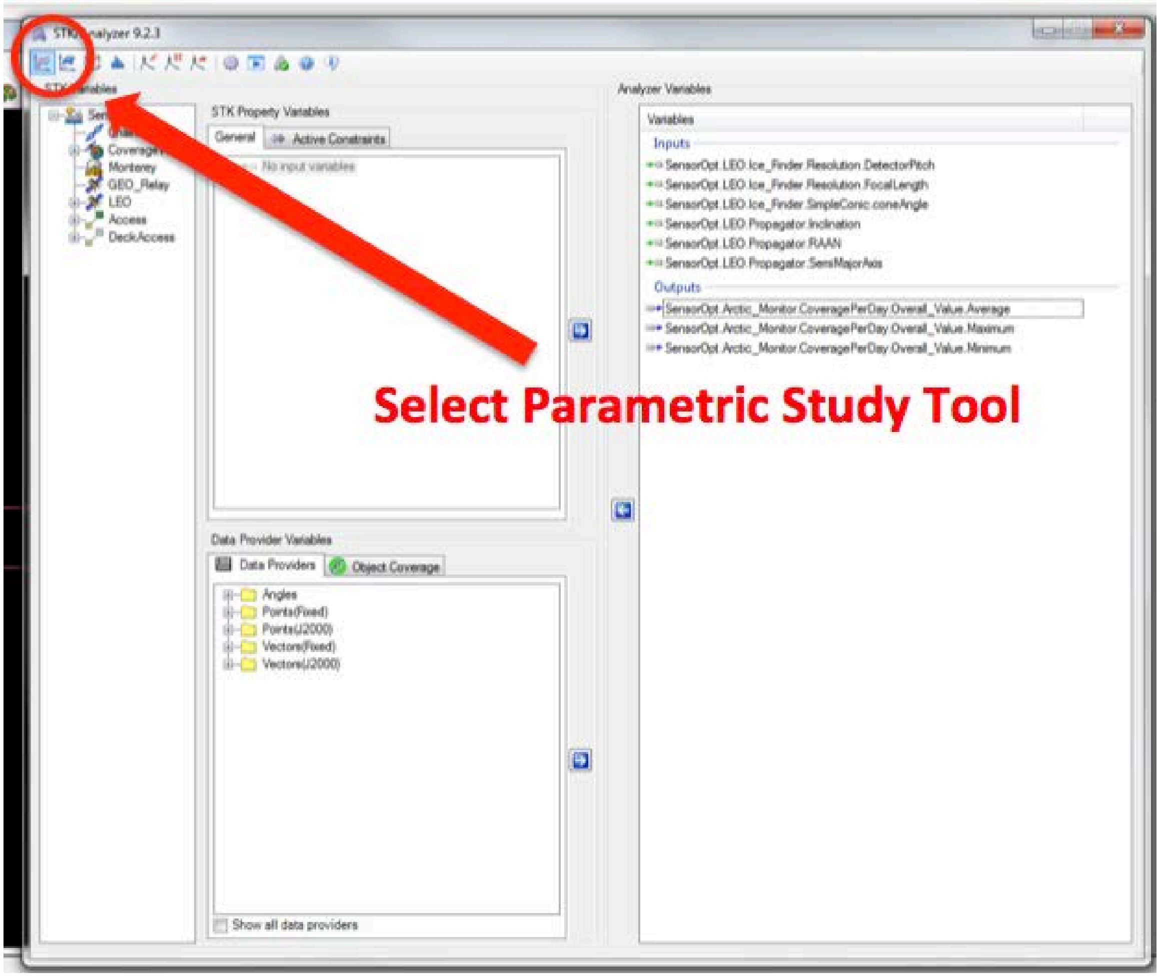

Figure 19. Select Parametric Study Tool

After the Parametric Study Tool is selected, the Parametric Study menu pops up as shown in Figure 20. This is where the constraints of the Design Variables are defined. For the purposes of the nadir facing sensor, the input variable was inclination. The output values were minimum, maximum and average. It should also be noted that the number of samples, in this case 10, is extremely important. This directly affects the step size and can change the simulation times exponentially. For a sample size of 10, the simulation times were ~10 minutes for each run. Also, it is important that the analysis period, in this case 7 days, is setup correctly to avoid lengthy simulation times or potential computer crashes due to the machine running for days on end.

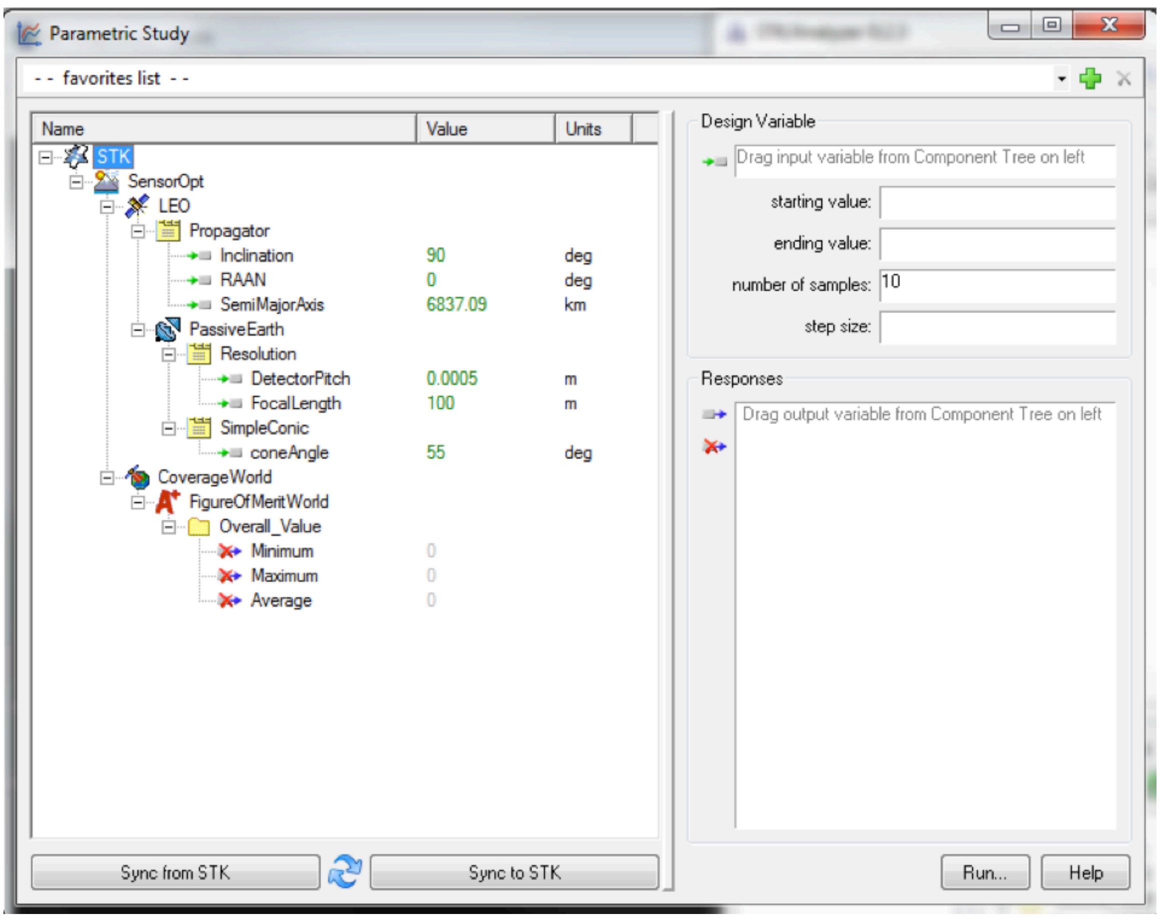

Figure 20. Parametric Study Tool Menu

When the Parametric Study Tool menu appears, the Design Variables can be set. For this thesis a broad range, 60^0 to 120^0 for inclination are used as starting and ending values, respectively, for inclination. One the Design Variables are set as shown in Figure 21, the scenario for inclination can be executed by selecting Run.

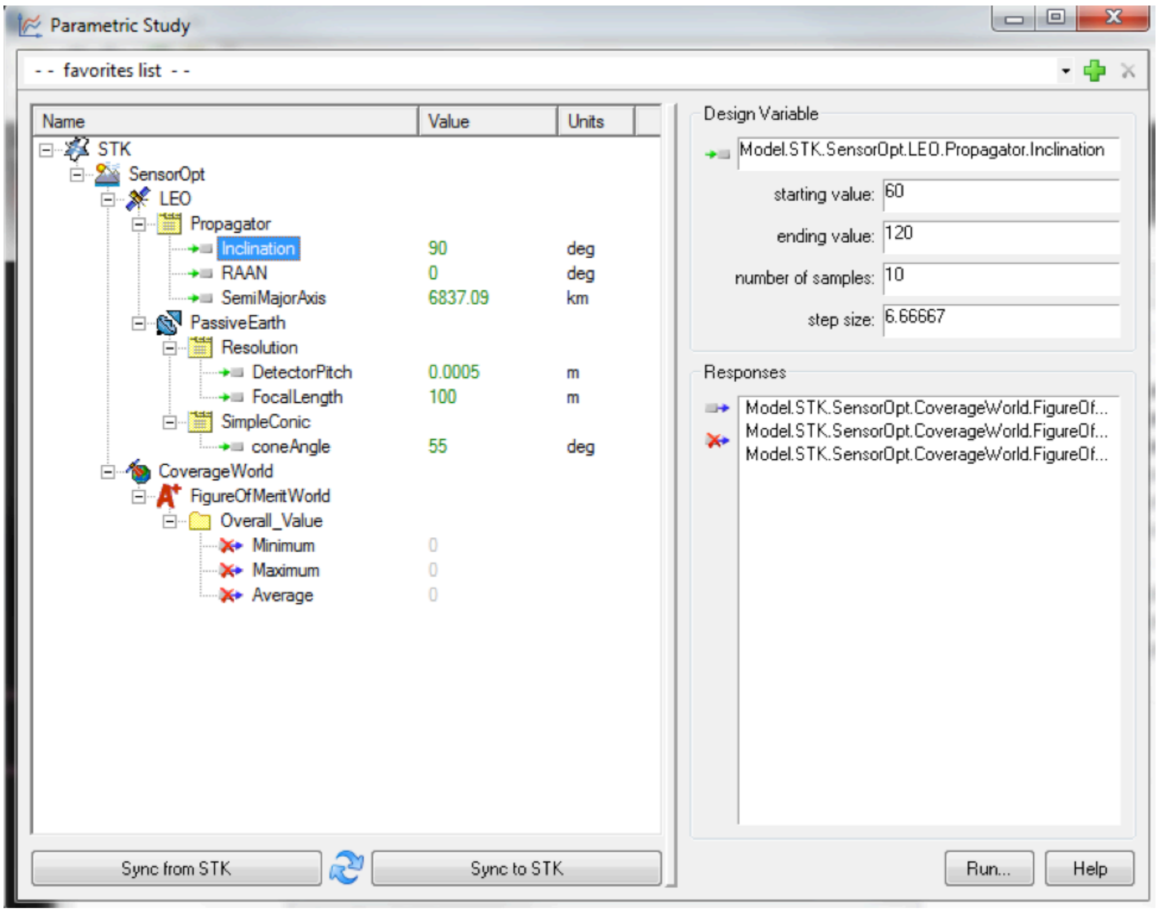

Figure 21. Set Broad Range for Inclination

It should be noted before reviewing the following data that in all of the following line plots, the blue line represents minimum values, the red line represents average values and the green line represents maximum values. Additionally, STK does not allow for the Y-axis to be labeled by the user, and places the default label of Minimum.Average.Maximum instead. In reality, the Y-axis represents the number of areas within the given latitudes the satellite will be able to fly over in a 24-hour period (e.g., number of revisits) in all of the following line plots. An example figure is shown in FigureX with labels to help the reader understand the plots in the remainder of the thesis.

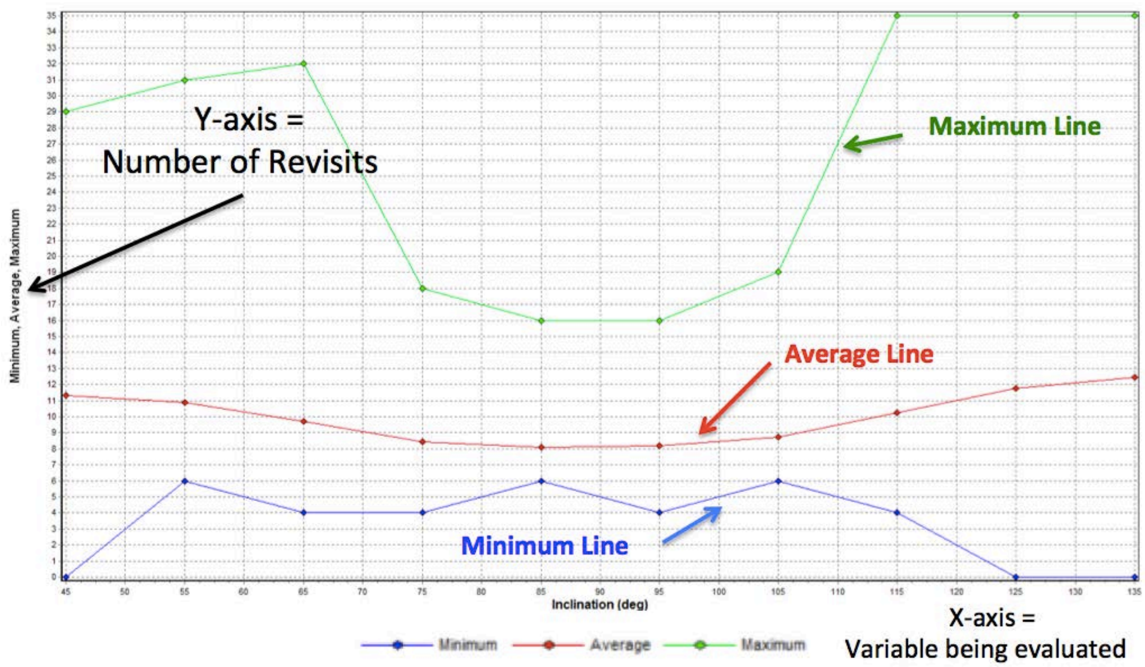

Figure 22. Example Plot

After the scenario is run, an output of inclinations vs. coverage possible was produced as shown in Figure 23. By looking at the plot for the maximum line, it can be seen that at 115^0 or greater, the number of areas covered reaches a plateau of 35 revisits. Thus, the inclination to be used for the remainder of the study will be 115^0.

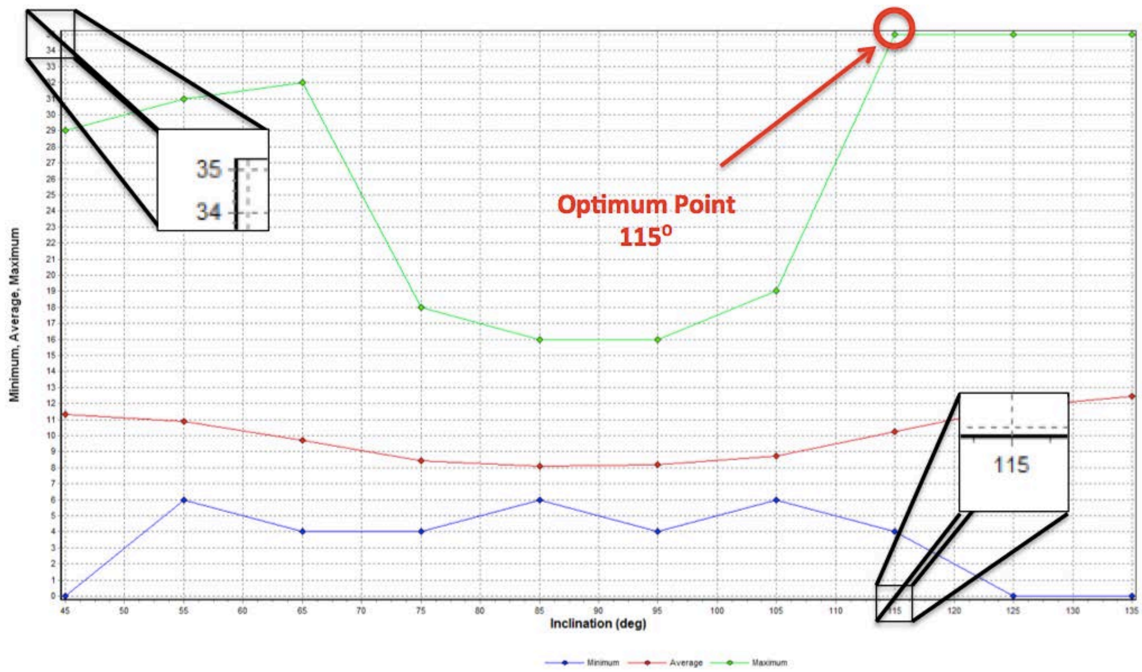

Figure 23. Output for Optimal Inclination

The next step is to determine the optimal value for the Right Ascension of Ascending Node (RAAN) and re-run the scenario to see if RAAN affects coverage as shown in Figure 24. The Design Variables are once again set up to encompass a broad range of values, in this case 0^0 to 360^0. The number of samples remains at ten and the step size is adjusted to 40 to accommodate the wider range of values. Once the Design Variables for RAAN are set, the Run option is selected to run the simulation.

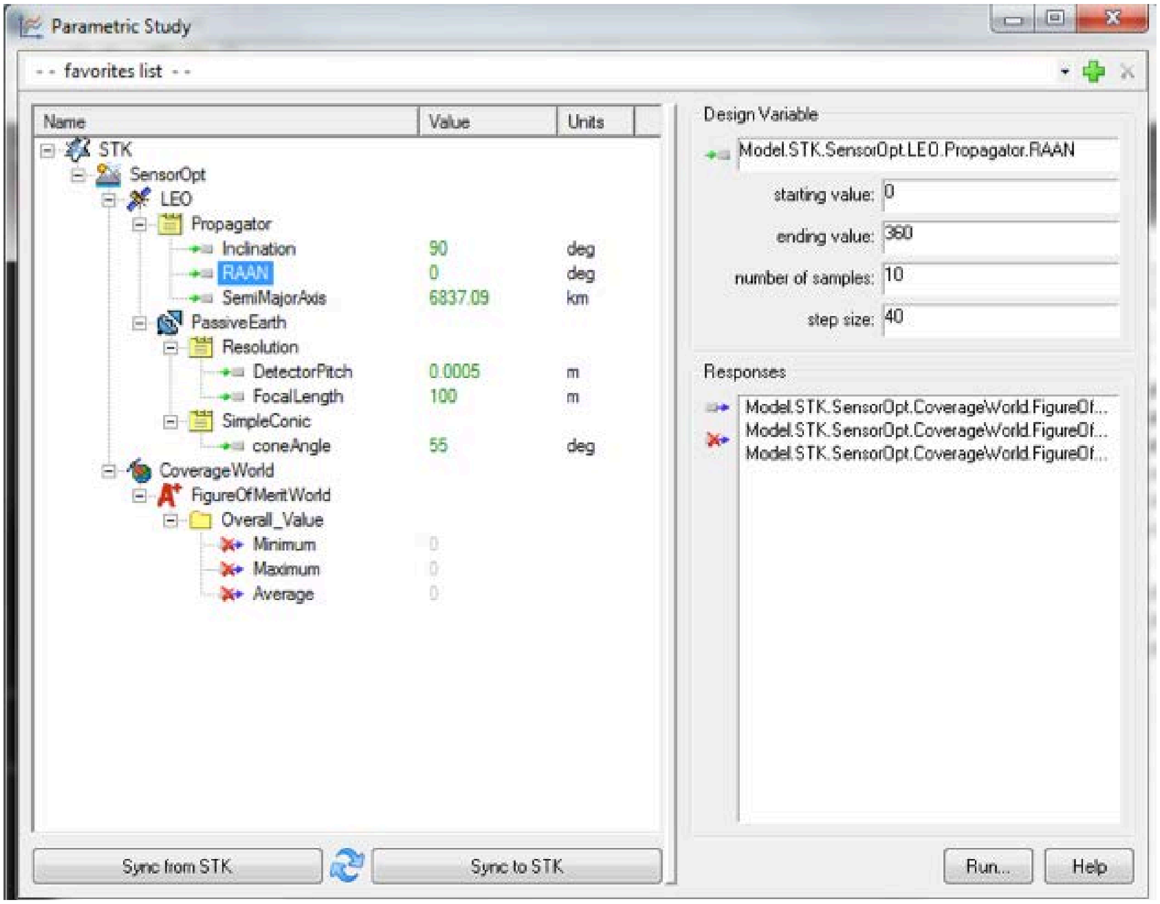

Figure 24. Set Broad Range for RAAN

When the scenario is re-run for broad range RAAN, an output is received. From the output depicted in Figure 25, it can be see that the uniform region of interest means RAAN variances have little effect on coverage. Note that if the region of interest had been constrained by a minimum and maximum longitude, then there would have been variance in the RAAN. What can be inferred from the output is that RAAN is not a factor that will contribute to optimizing the system.

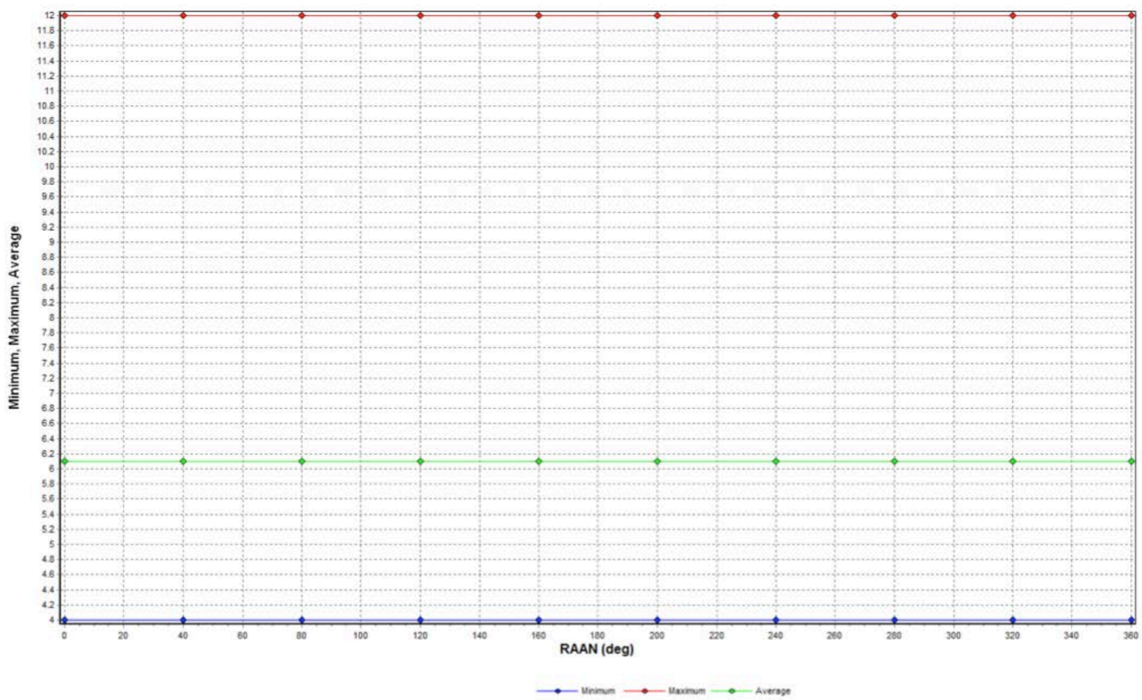

Figure 25. Optimal Output for RAAN

Once the optimal inclination and RAAN have been determined, in this case 115^0 and 0^0 respectively, the next step is to determine the semi-major axis. The semi-major axis is what defines the altitude of the orbit and is measured from the center of the Earth to the point in space where the orbit is. There are typically two measurements for an orbit, the semi-major axis and semi-minor axis, however since the notional LEO orbit being investigated in this thesis is a near circular orbit, the semi-minor axis does not need to be determined. Figure 26 demonstrates the semi-major and semi-minor axes. Figure 27 shows the setup in STK to determine the semi-major axis. It should be noted that the distance from center of Earth to surface at equator is 6378km (Wertz and Larson 1991, 118). When the outputs for the semi-major axis are presented, the distance from the center of the Earth to the equator should be subtracted form the distance of the semi-major axis to find the altitude of the orbit in kilometers.

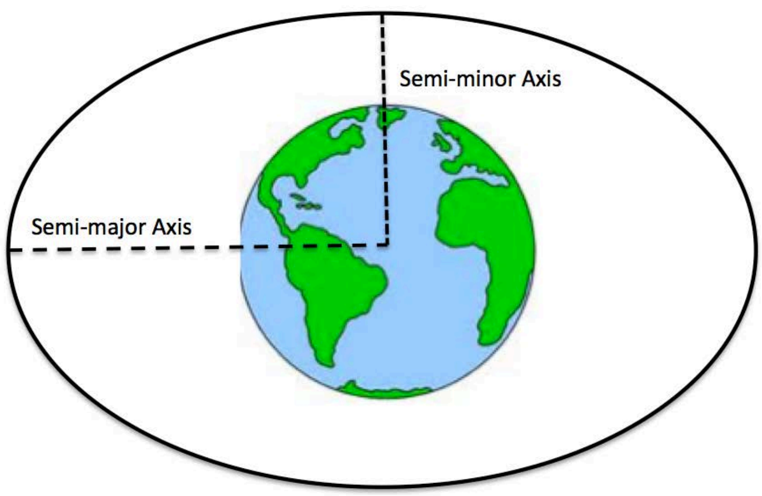

Figure 26. Semi-major vs. Semi-minor Axis

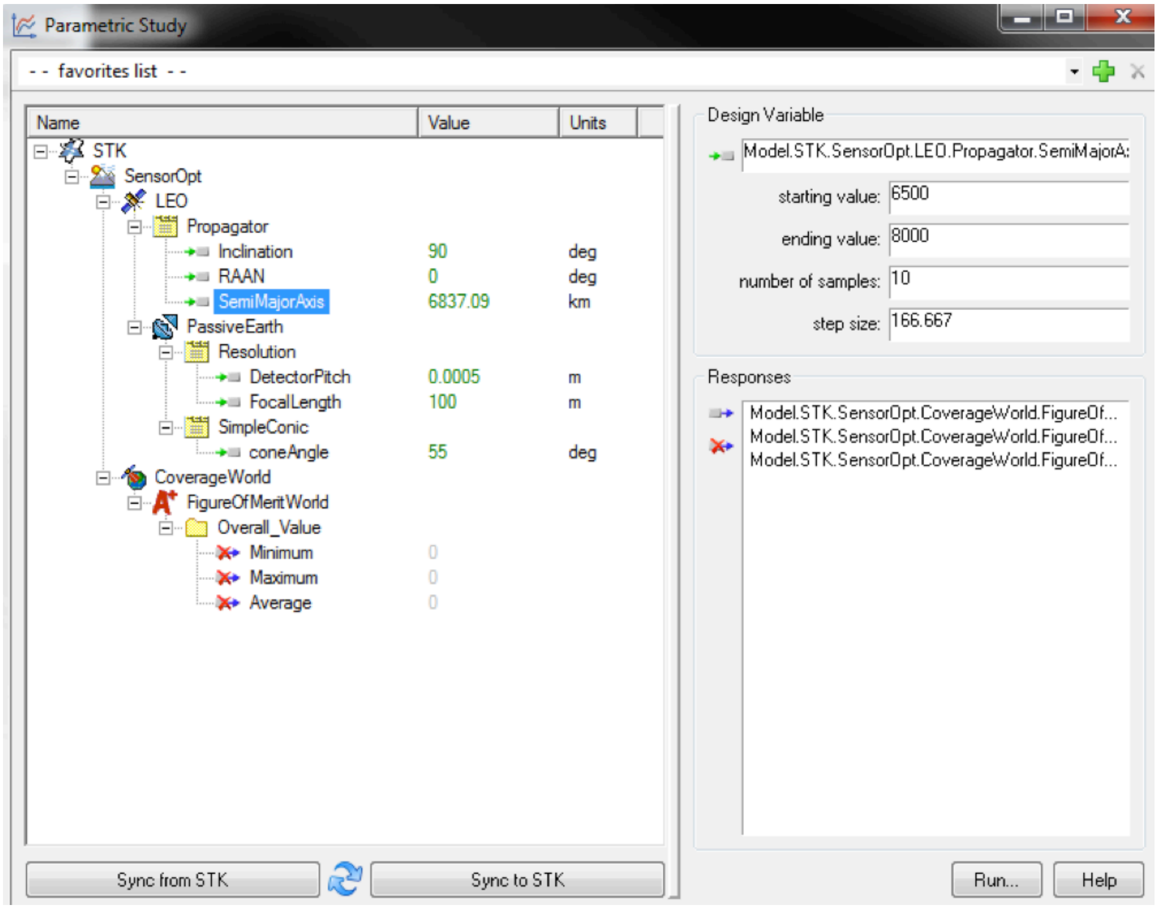

Figure 27. Set Broad Range for Semi-major Axis

Once the broad range for semi-major axis is set, in this case a starting value of 6500km and the ending value of 8000km, the scenario is rerun and the output is exhibited in Figure 28.   As it can be seen, as space vehicle altitude increases, ground coverage increases at a linear rate. This is expected as no sensor parameters or target sizes have been considered yet al.so due to this fact, there is no optimal point in Figure 28. The biggest takeaway from this figure is that as altitude increases, the number of revisits increases as well.

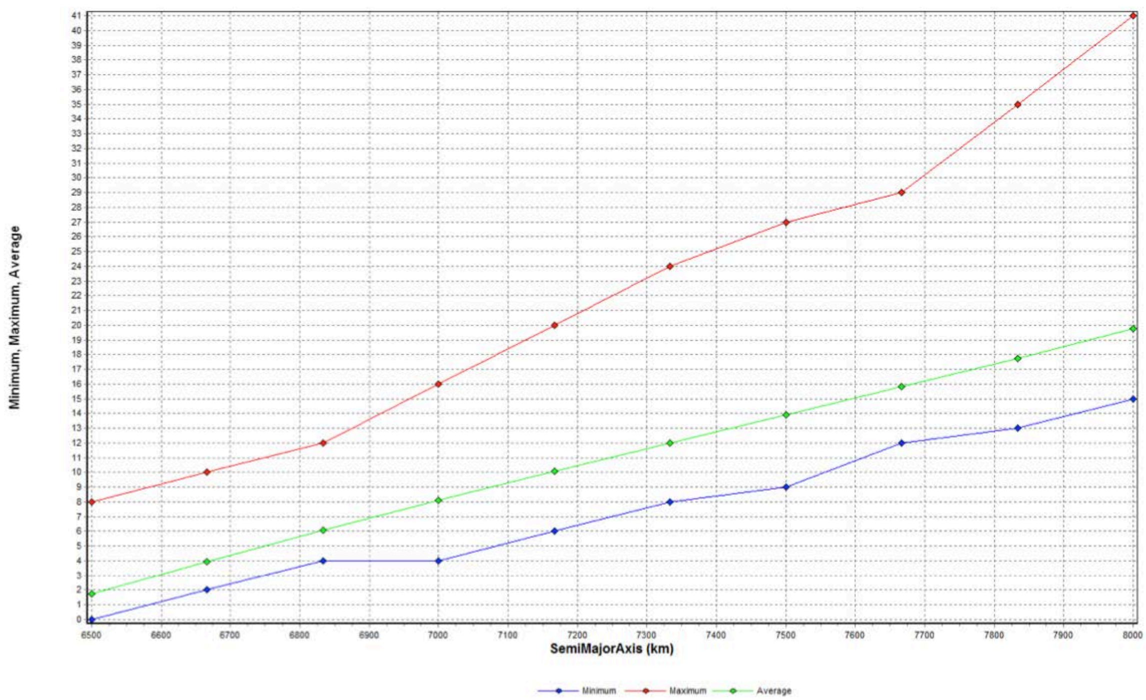

Figure 28. Output of Broad Range for Semi-major Axis

Now that it has been shown that coverage will increase as altitude increases in general, the nadir sensor parameters must be adjusted to determine the how sensor characteristics affect the semi-major axis. Until this point, Design Variables for inclination, RAAN and semi-major axis were adjusted to find optimal outputs. The sensor parameters under the Passive Earth menu were not adjusted. The sensor parameters for the optical sensors include Detector Pitch (e.g., pixel size), Focal Length and Cone Angle.

Detector Pitch determines how large each pixel on the optical sensor is. An example of large vs. small detector pitch is shown in Figure 29, where each inner square represents a pixel. As the pixel size shrinks, it can be seen that more pixels can fit on the sensor, yielding a better image.

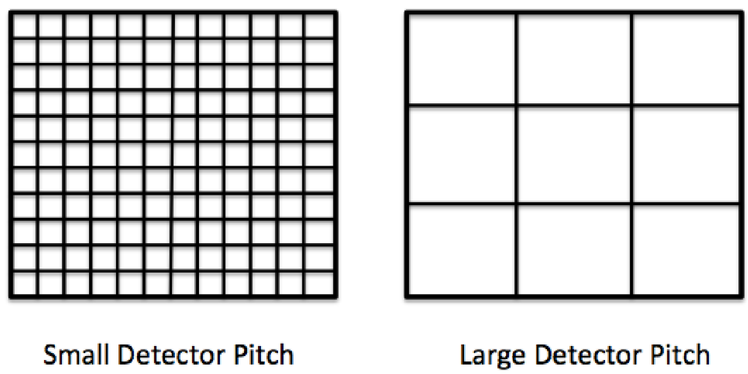

Figure 29. Small vs. Large Detector Pitch

Focal length in an optical system is the measure of how strongly the system can converge or diverge light. In the case of space optical systems, such as ones in this thesis, the subject (e.g., the Earth or debris) is considered far away. Due to this fact, a longer focal length and narrower view angle or cone angle is required to provide sufficient magnification. Cone angle refers to the imaginary cone created from the front of the sensor to the field of view on the Earth. An example of cone angle is shown in Figure 30.

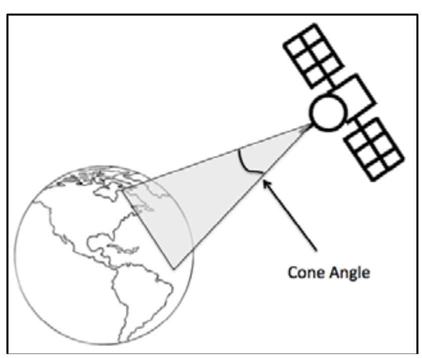

Figure 30. Cone Angle

Finally, resolution is referred to in this thesis as well. Resolution is affected by detector pitch and focal length and refers to the ability to detect an object of a certain size in an image. For example, a 2-meter resolution image would allow two objects 2-meters in size to be differentiated in an image. (Wertz and Larson 1991, 180)

The values for detector pitch, focal length and cone angle were adjusted using STK to find the optimal sensor parameters vs. semi-major axis. These values remained at the default STK values of Detector Pitch =0.0005, Focal Length = 100m and Cone Angle = 55 as shown in Figure 31 while the orbital parameters were being determined.

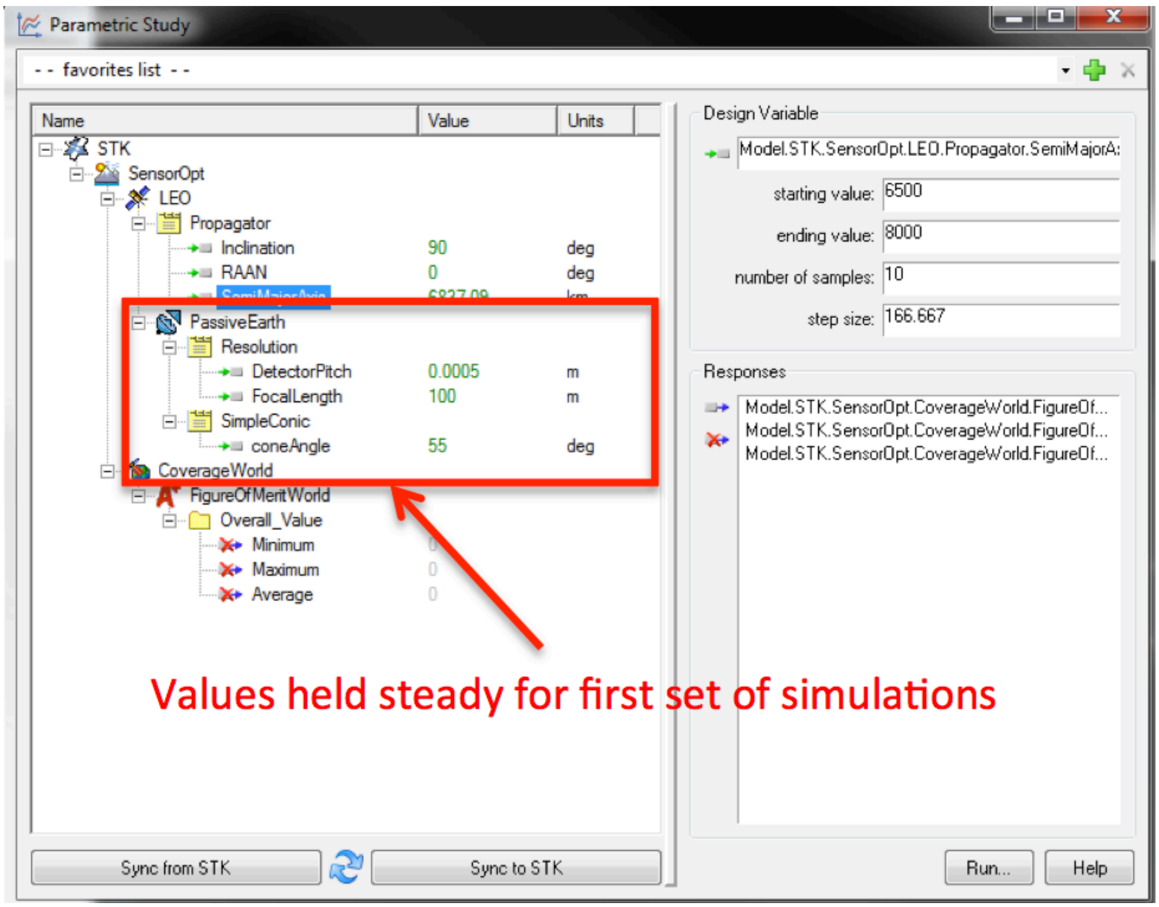

Figure 31. Passive Earth Values Held Steady

To develop a general understanding for how a nadir sensor will affect the semi-major axis, a very broad range of sensor parameters were used. Resolution was constrained to 5m, meaning an object 5m in size on the surface of the Earth can be

differentiated from another 5m object on the Earth. Also, the focal length was set to 100m. In reality, a 100m focal length would require a very large aperture (e.g., lens) on the sensor, and would not be feasible for a hosted payload. However, the focal length was chosen so a starting point could be established as shown in Figure 32. Looking at Figure 32, it can be seen that as altitude increases, ground coverage increases at a non-linear rate, until it reaches a peak. This peak on the green line, at approximately 6945km, would be the optimum point if a 100m aperture was used. Another item to note is the large trough in the blue line at the optimum point. Upon investigation, it was discovered that this was attributed to the number of samples taken. If simulation time had been increased, the trough would have not been shown. In this case though, the simulation took approximately 10 minutes, and it was determined that a second simulation was unnecessary for the unrealistic aperture size.

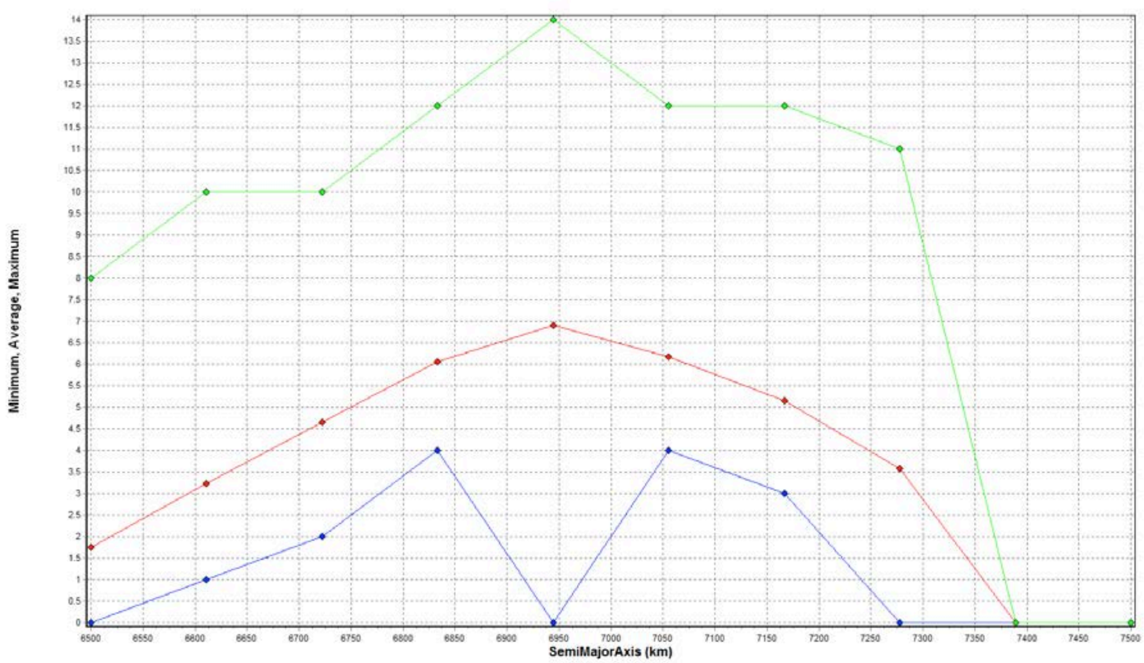

Figure 32. Output of Semi-Major Axis with Nadir Sensor Constrained to 5m Resolution, 100m Focal Length

To continue the analysis in finding the optimum semi-major axis, other focal lengths were considered as well. In Figure 33, the focal length is set to 50m while holding other factors steady.

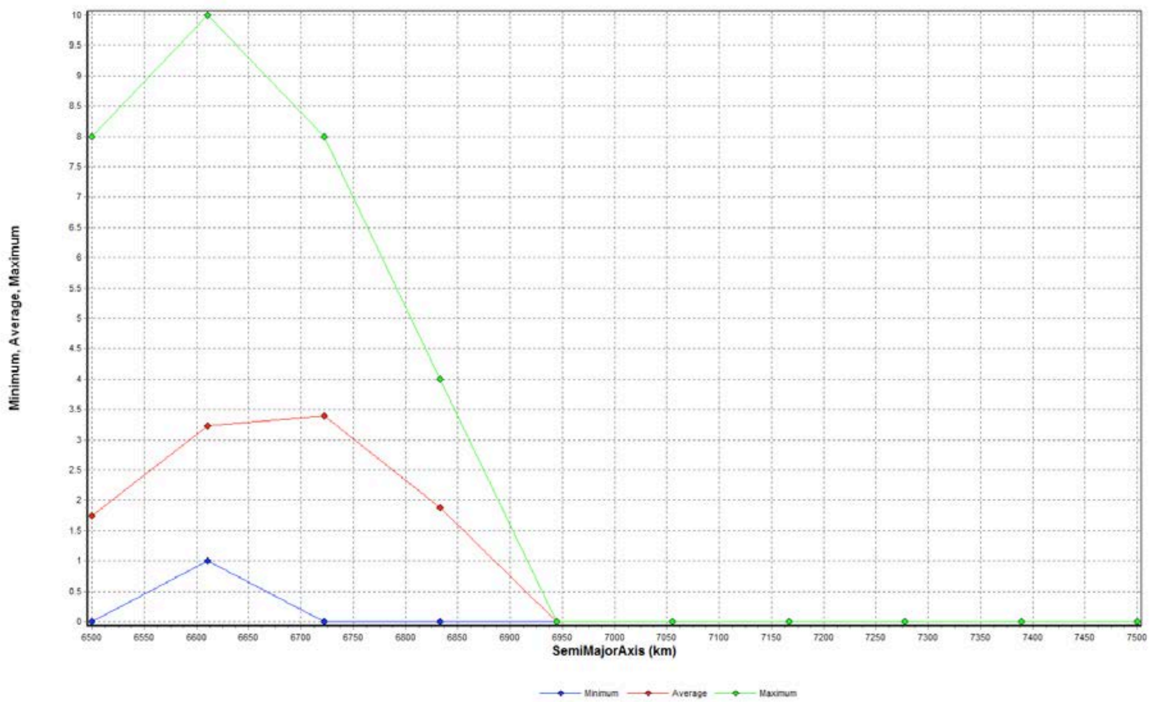

Figure 33. Output of Semi-Major Axis with Nadir Sensor Constrained to 5m Resolution, 50m Focal Length

By adjusting the focal length to 50m, the optimal semi-major axis has shifted to a lower altitude of 6610km on the green line. This altitude is only about 300km above the surface of the Earth and not a very usable orbit. In addition, 50m for focal length is still a large value for a hosted payload. In the next scenario, the focal length is adjusted to 25m. This is shown in Figure 34.

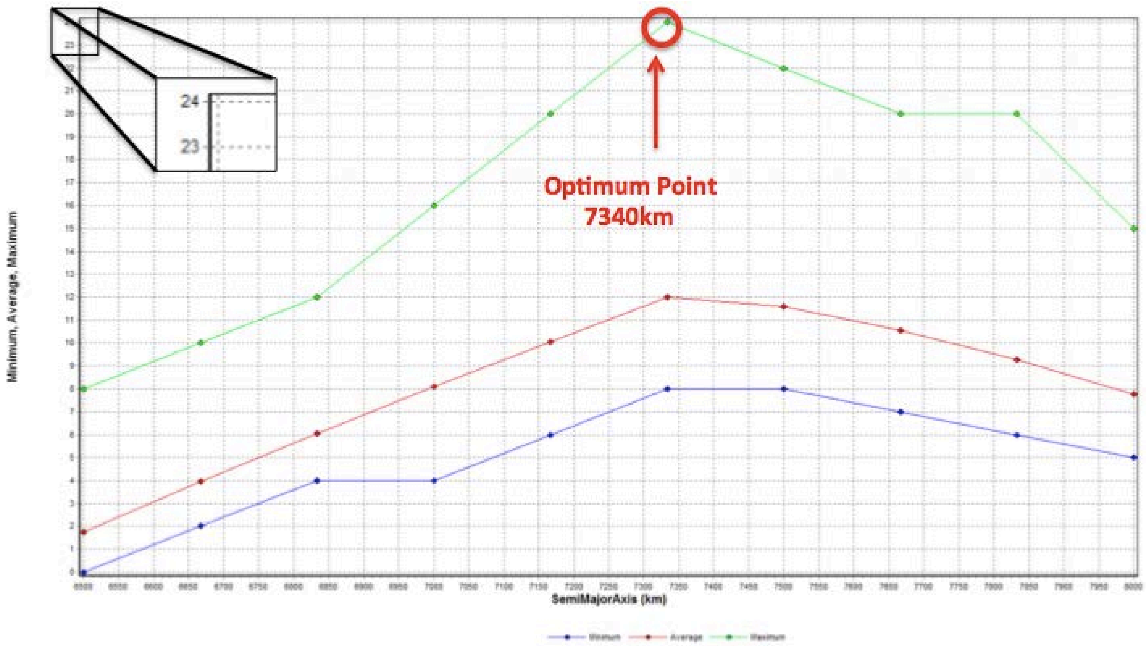

Figure 34. Output of Semi-Major Axis with Nadir Sensor Constrained to 5m Resolution, 25m Focal Length

It can be seen that with the smaller focal length, the orbit is now starting to shift towards a more usable altitude. In this case the optimal point on the green line lies at 7340km. In the next scenario, focal length was adjusted to 10m. In addition, the pixel pitch, which is the size of the pixels on the sensor, was adjusted to $5 * 10^{-6}$m vs. $5 * 10^{-5}$m. The output is shown in Figure 35.

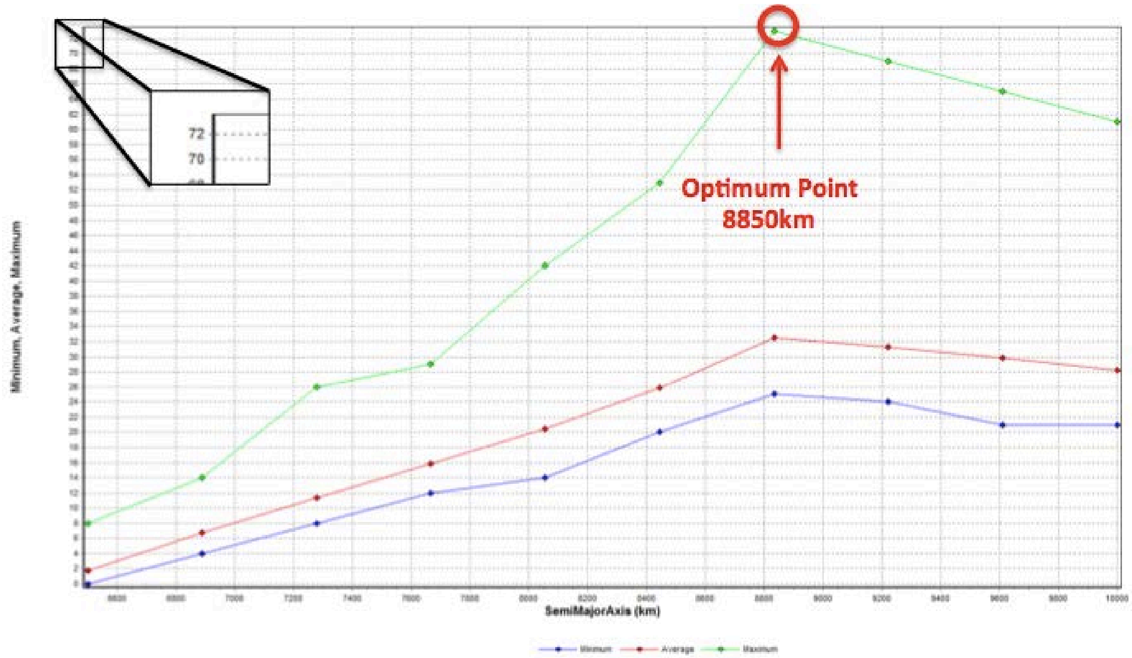

Figure 35. Output of Semi-Major Axis with Nadir Sensor Constrained to $5 * 10^{-6}$m Pixel Pitch and 10m Focal Length

The output for this scenario places the optimal point for the semi-major axis at approximately 8850km. After this point, there is degradation in system performance as can be seen by the decay of the green line. While these results are beginning to look promising, it should be noted that since a 10m aperture is still a very large size, requiring a very large lens, the results here are still not optimal for the purposes of a hosted payload.

In the next scenario, focal length was set to 1m and pixel pitch was set to $5 * 10^{-7}$m. The results are depicted in Figure 36.

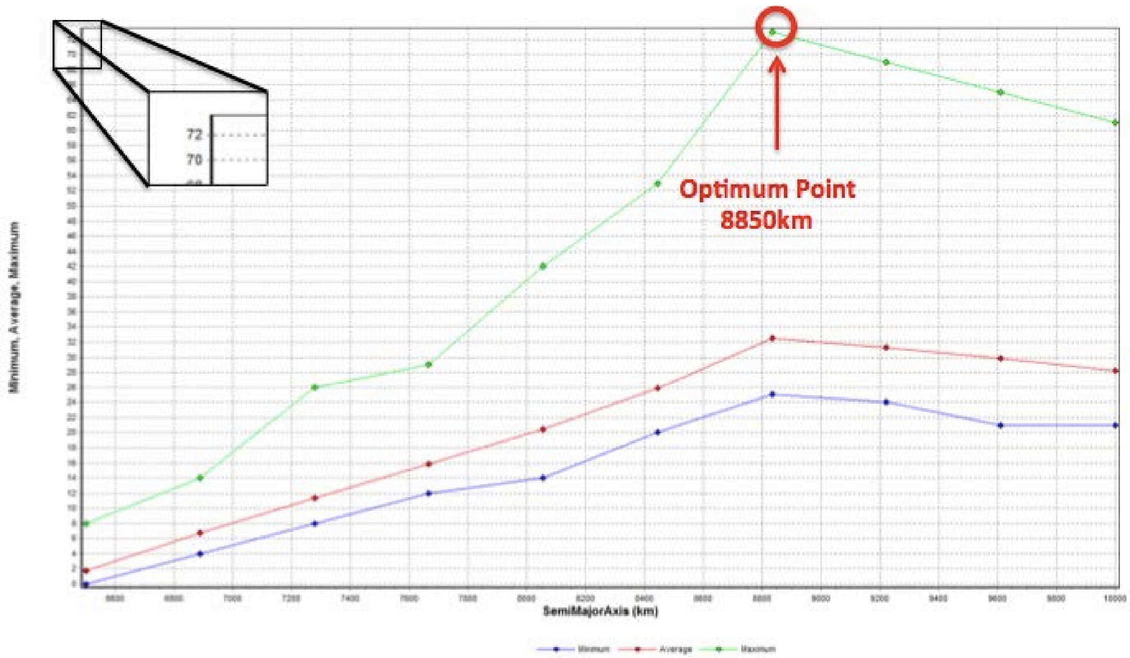

Figure 36. Output of Semi-Major Axis with Nadir Sensor Constrained to $5 * 10^{-7}$m Pixel Pitch and 1m Focal Length

This scenario presented an interesting result. Although the focal length was decreased by 9 meters, by decreasing the pixel pitch by an order of magnitude the net result was exactly the same curve as the previous scenario depicted in Figure 35. This is good to see since it shows that similar performance from a sensor can be achieved by adjusting pixel pitch while making the focal length more realistic for a hosted payload.

For the next scenario, the focal length was held to 1m and pixel pitch was held to $5 * 10^{-7}$m. However, the resolution of the sensor was adjusted from 5m to 1m, meaning that a 1m object on the ground could be differentiated from another 1m object. The results of this scenario are shown in Figure 37.

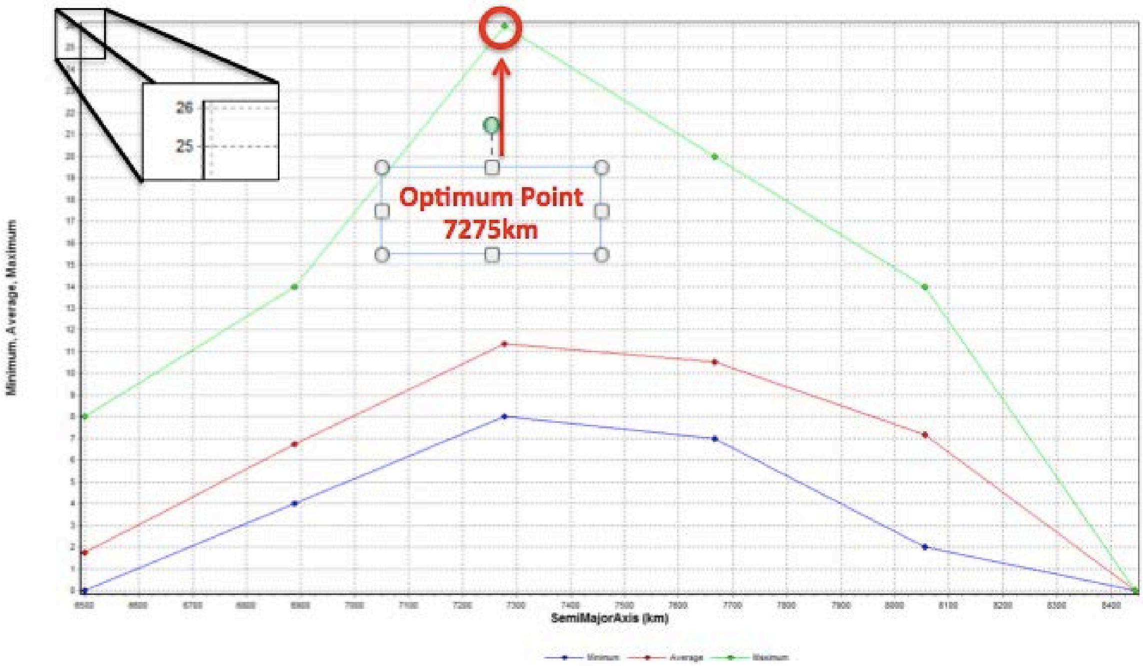

Figure 37. Output of Semi-Major Axis with Nadir Sensor Constrained to $5 * 10^{-7}$m Pixel Pitch, 1m Focal Length and 1m Resolution

By holding the focal length and introducing the new resolution into the scenario, there is a decrease in performance as far as number of times a particular point on Earth is seen (e.g., the Y-axis). However, the performance is not poor; on the contrary the sensor performance is adequate for a hosted payload. From the green line, it can be seen that the performance for a sensor this size will provide 26 revisits at the optimal point of 7275km. In addition, 7275km is in the usable range semi-major axis of LEO orbits and will provide optimal coverage of the Earth.

In the next scenario, focal length was set to 0.5m and pixel pitch was held at $5 * 10^{-7}$m to see if decreasing focal length affects the semi-major axis any further. The results are shown in Figure 38.

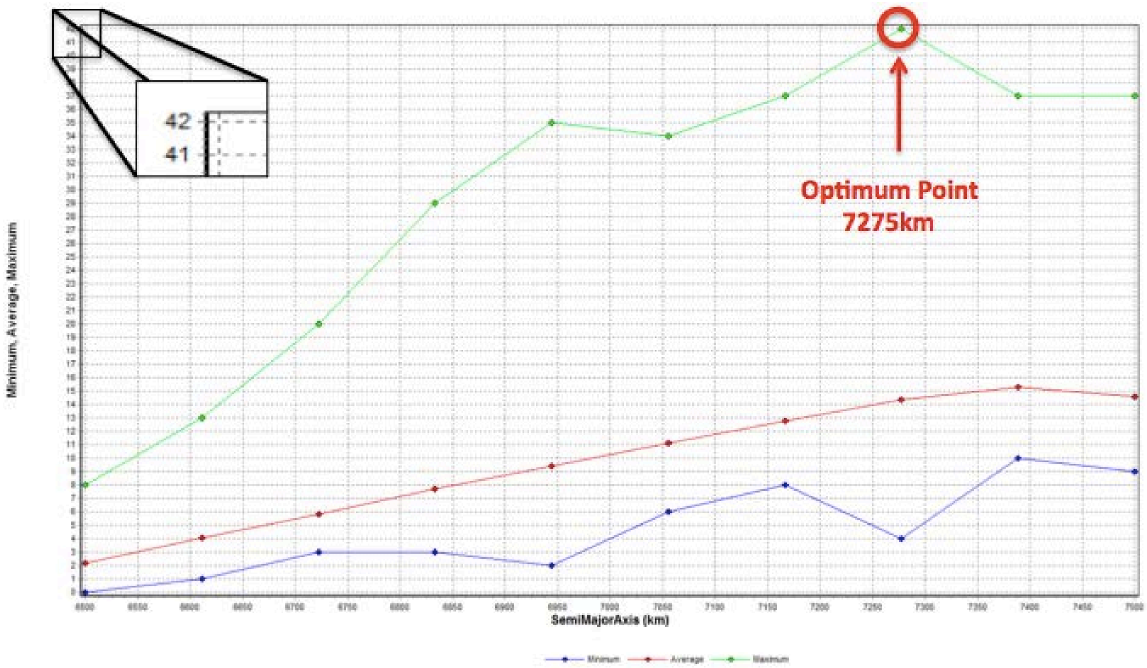

Figure 38. Output for Semi-major Axis, Constrained to 1m Resolution, 0.5m Focal Length, $5 * 10^{-7}$m Pixel Pitch

By shrinking the focal length and holding to the new resolution in the scenario, there is an increase in performance as far as number of times a particular point on Earth is seen (e.g., the Y-axis). From the green line, it can be seen that the performance for a sensor this size will provide 42 revisits at the optimal point of 7275km. It is important to note that the 7275km did not change from the previous scenario to this scenario being the optimal point. This means that the simulations have found the optimal distance for the semi-major axis at 7275. For the purposes of this thesis, the 1m focal length will be used as a baseline in the remainder of the analysis, with adjustments made as necessary to facilitate the analysis.

Since each simulation up to this point has taken upwards of 30 minutes to run, this researcher concluded that additional runs for finding the optimal semi-major axis were not required for academic purposes. However, the author of this thesis was interested to see what the results would be if no constraint were placed on resolution, meaning the sensor could see everything from space as if it there were no distortion. The thought was that if sensor resolution were not a concern, performance would increase. To test this scenario, one final run was done with results shown in Figure 39.

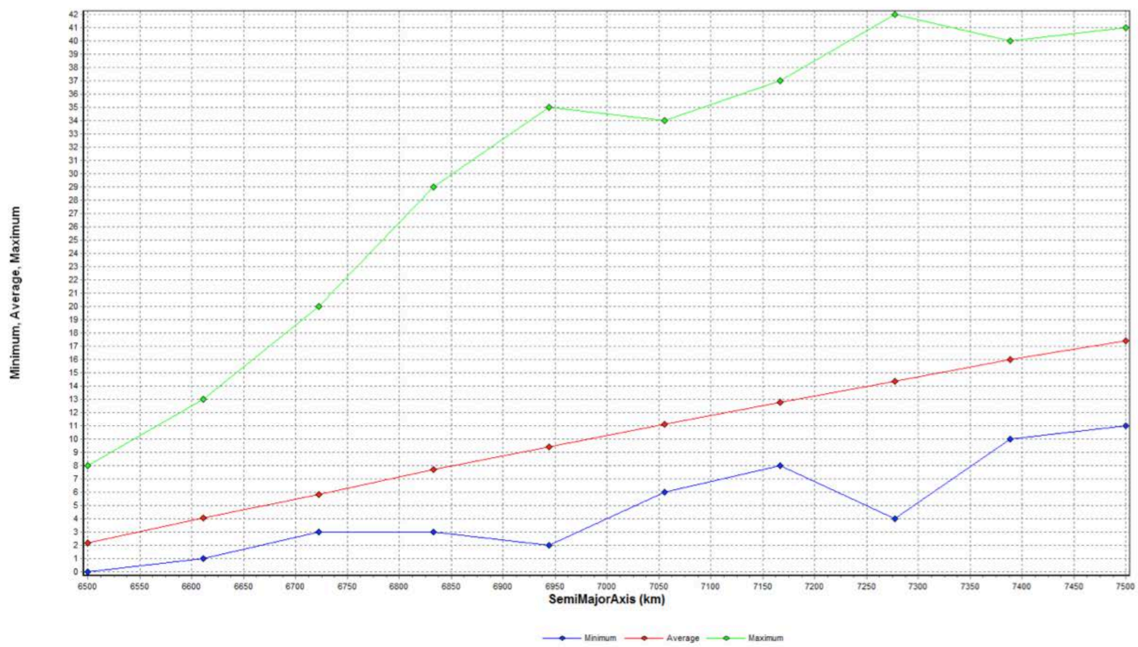

Figure 39. Output for Semi-major Axis, No Resolution Constraint, 0.5m Focal Length, $5 * 10^{-7}$m Pixel Pitch

By looking at the results in Figure 39, it can be seen that there is better sensor performance, but only slightly. This goes to show that having infinite capability, such as unlimited resolution, will not necessarily provide infinitely better results.

Once various outputs for semi-major axis were analyzed by adjusting for various parameters and a semi-major axis of 7275km was determined to be the optimal point, the next step was to see how inclination would affect the results. Until this point, the variables of inclination, semi-major axis, and RAAN have all been evaluated independently. At this point, they will be evaluated against each other to see if changing sensor parameters against two orbital parameters has a significant effect on which type of nadir sensor to specify. To begin this section of the analysis, a carpet plot was generated by performing a 2-dimensional parametric study of inclination vs. semi major axis. The sensor parameters were held to what was shown in Figure 39.

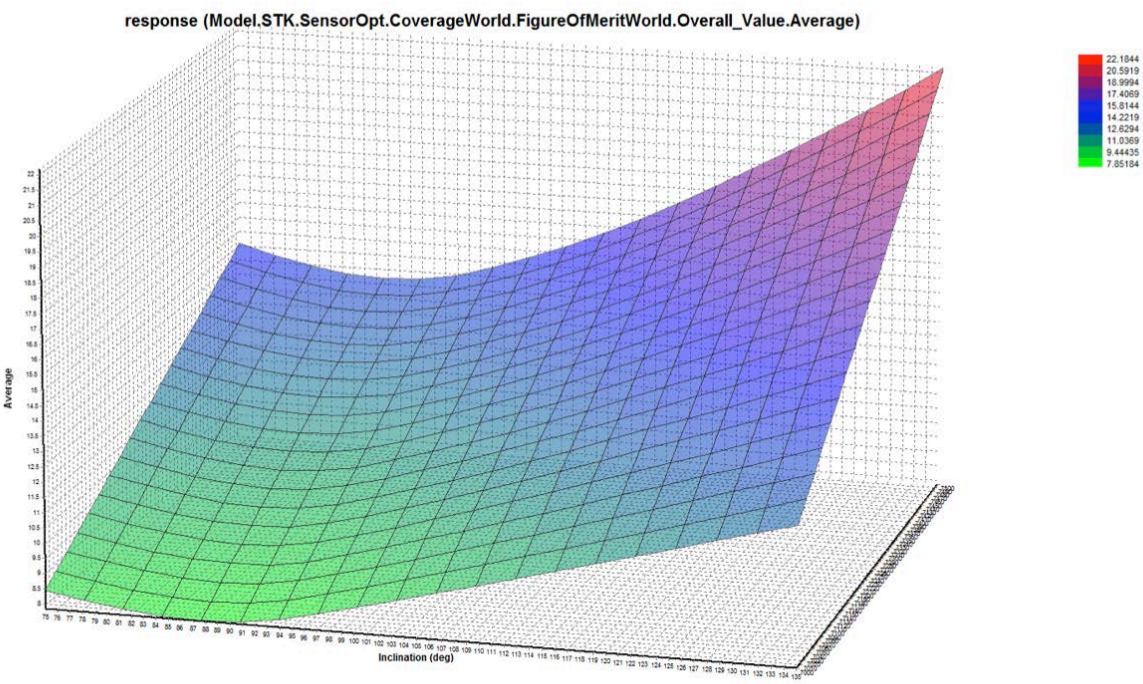

Figure 40. 3-Dimensional Plot of 2-Dimensional Parametric Study for Inclination vs. Semi-major Axis with No Resolution Constraint, $5 * 10^{-7}$m Pixel Pitch and 1m Focal Length

While it is difficult to ascertain without an ability to zoom in on the image, the reader should understand that in Figure 40, the plot shows the inclination on the X-axis, number of revisits on the Y-axis and distance for the semi-major axis on the Z-axis. If one zooms in on a computer, it can be seen that the optimal point (top right red corner of

the plot) lies at X=130^0, Y=22, Z=7275km. This means that when the two variables are evaluated against each other, with sensor parameters factored in, the optimal point for inclination actually shifts by 15^0 from 115^0 to 130^0, and the number of revisits changes. The number of revisits does not affect the study very much, however, the change in inclination will.

To see if adjusting focal length and adding the resolution constraint back in has any affect when evaluating inclination vs. semi-major axis, the next carpet plot is generated with a focal length of 1m, pixel pitch of $5 * 10^{-7}$m and a 1m resolution constraint. The results are shown in Figure 41.

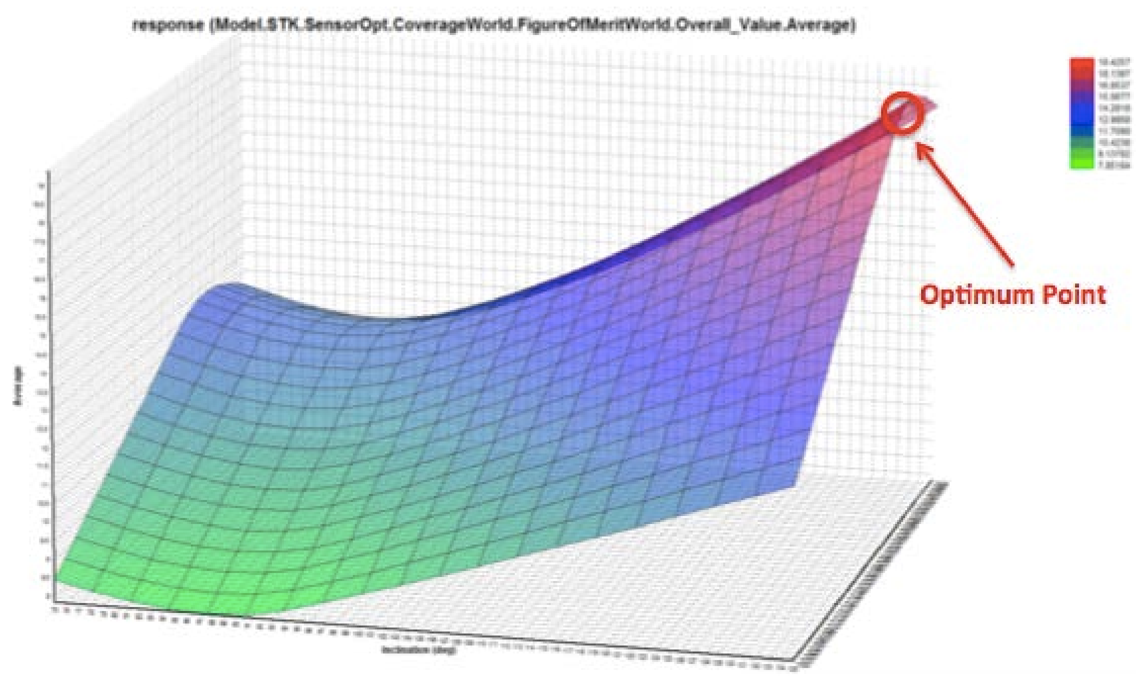

Figure 41. 3-Dimensional Plot of 2-Dimensional Parametric Study for Inclination vs. Semi-major Axis with 1m Resolution Constraint, $5 * 10^{-7}$m Pixel Pitch and 1m Focal Length

By introducing the resolution constraint back into the simulation and increasing the focal length, the optimal point now has shifted a bit. The optimal point now lies at X=133^0, Y=19 and Z=7390km. If the vertex of the carpet plot in Figure 41 is shifted to the center, then one can better visualize the data. This is what is depicted in Figure 42.

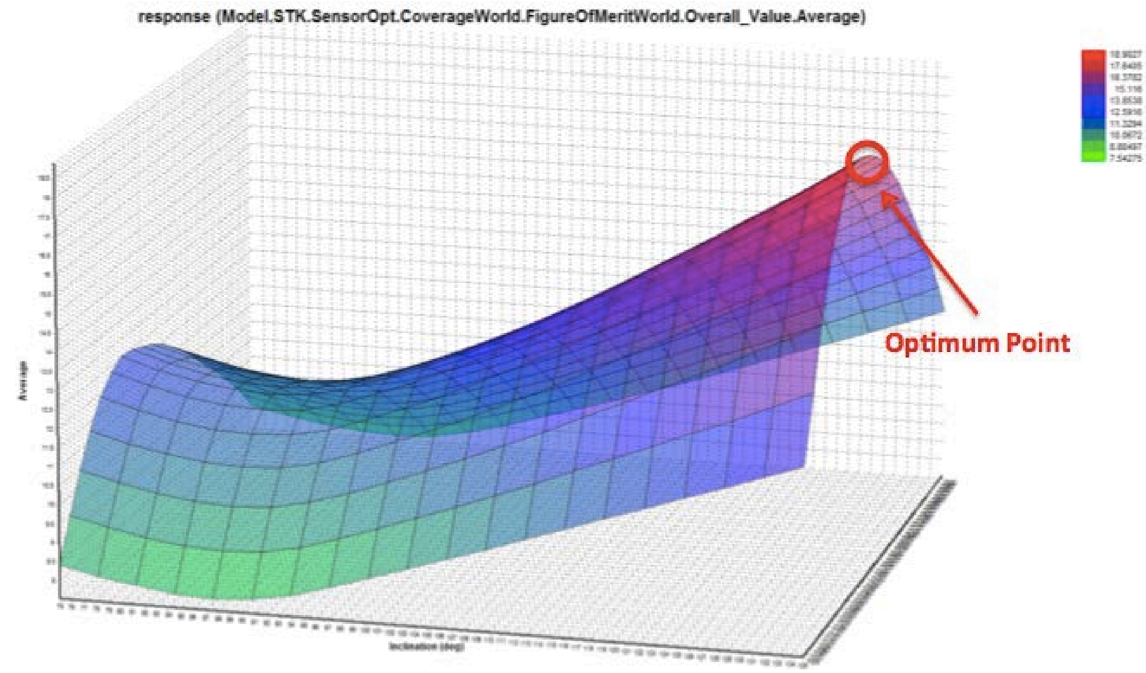

Figure 42. 3-Dimensional Plot of 2-Dimensional Parametric Study for Inclination vs. Semi-major Axis with 1m Resolution Constraint, $5 * 10^{-7}$m Pixel Pitch, 1m Focal Length and Vertex Centered

By centering the vertex, the decay in performance as the Z axis increases can be better seen, however, to further refine the data, the lower bound for inclination (X-axis) was set to 120^0. This resulted in what is shown in Figure 43.

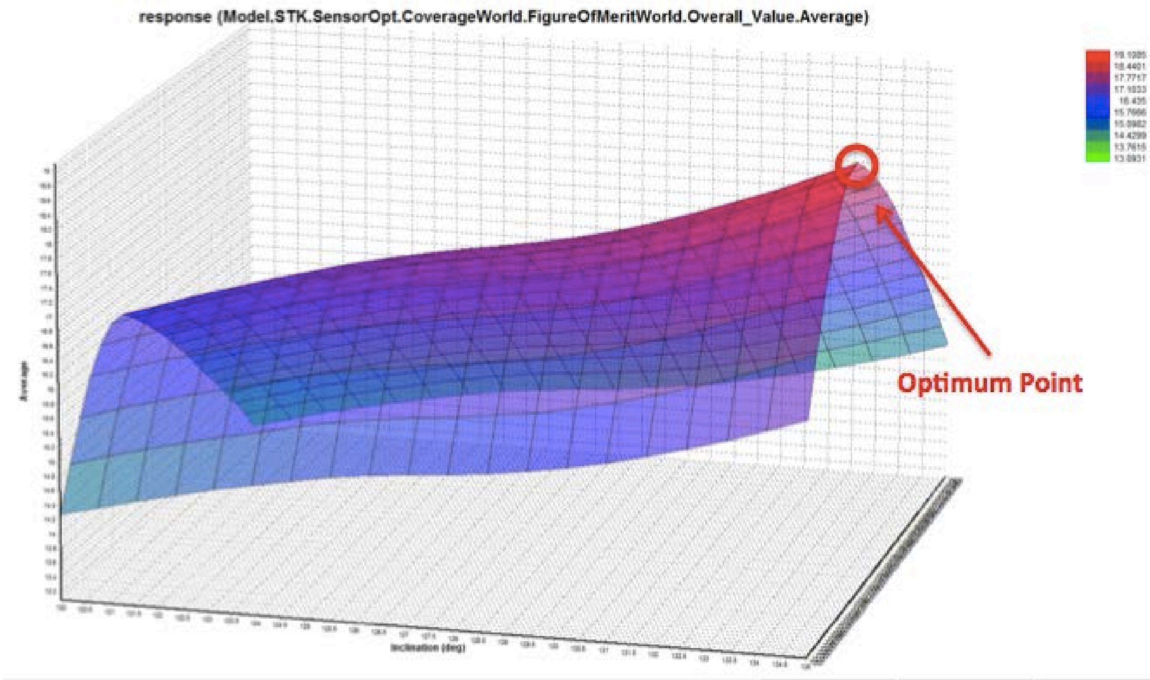

Figure 43. 3-Dimensional Plot of 2-Dimensional Parametric Study for Inclination vs. Semi-major Axis with 1m Resolution Constraint, $5 * 10^{-7}$m Pixel Pitch, 1m Focal Length, Vertex Centered and X-axis Lower Bound Set to 120^0

Running the scenario again with the data further confined, the final optimal parameters resulted in 135^0 inclination and the semi-major axis changing to 7275km. This was a direct result of a smaller subset of data being evaluated.

For the remainder of the analysis, these values will be used for inclination and semi-major axis unless it was necessary to change them for the analysis. To better give the reader an understanding of the final data, a contour plot was generated, which is easier to read in a printout. This is shown in Figure 44.

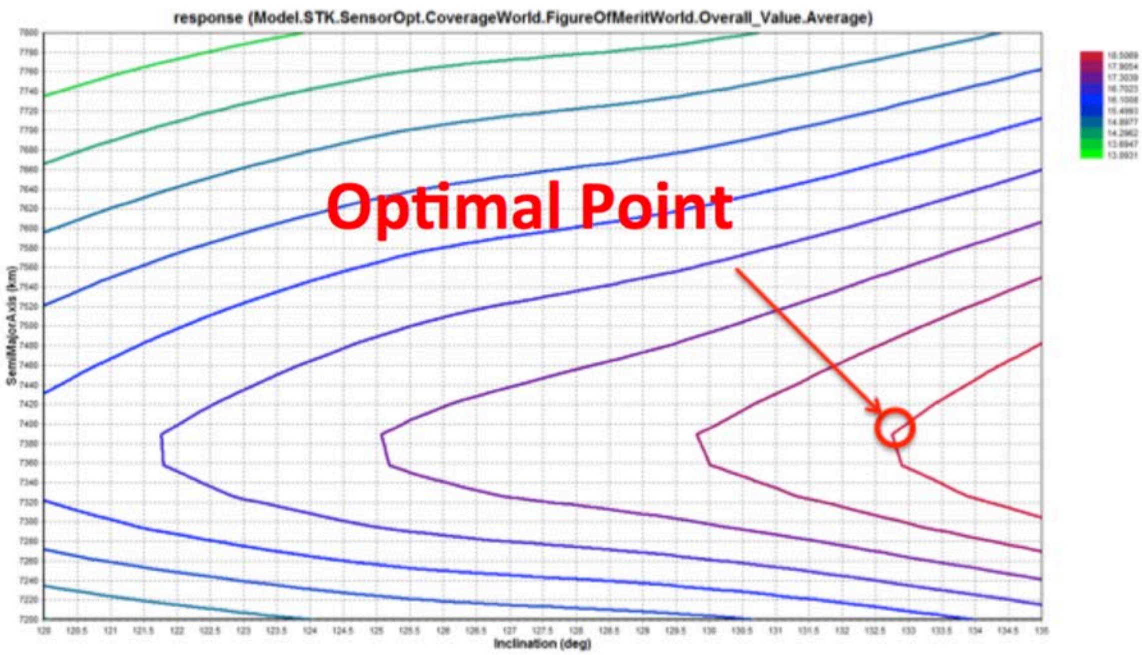

Figure 44. Contour of 2-Dimensional Parametric Study for Inclination vs. Semi-major Axis with 1m Resolution Constraint, $5 * 10^{-7}$m Pixel Pitch, 1m Focal Length, Vertex Centered and X-axis Lower Bound Set to 120^{0}

Looking at the contour plot, the reader can better see the red line where the optimal point lies.

For the next part of the simulations, the optimal pixel size was investigated. Once again, the parametric study tool was used as shown in Figure 45.

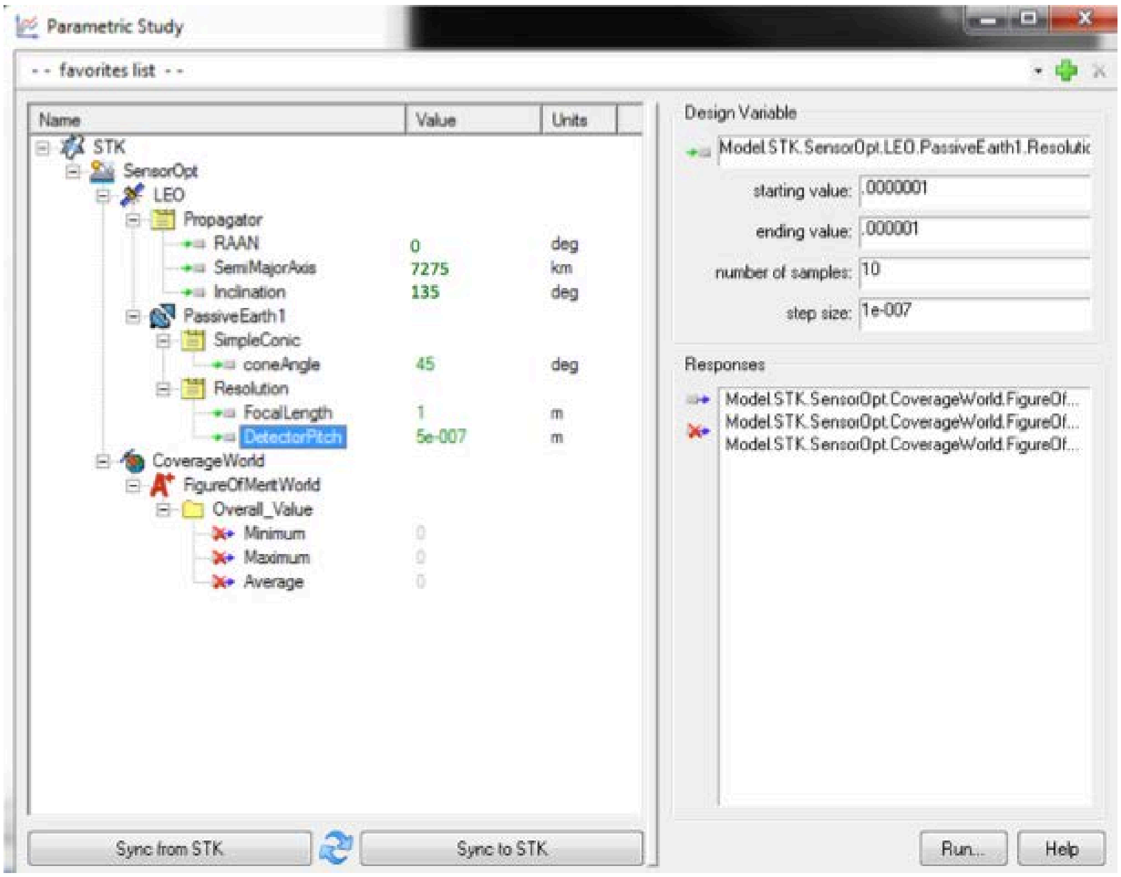

Figure 45. Parametric Study Menu for Optimal Pixel Size

The design variables for pixel pitch, or DetectorPitch in STK, are given a starting and ending value as shown, $1 * 10^{-7}$ and $1 * 10^{-6}$, respectively.

Once the scenario is setup, it is run to output the optimal pixel size. The results can be seen in Figure 46.

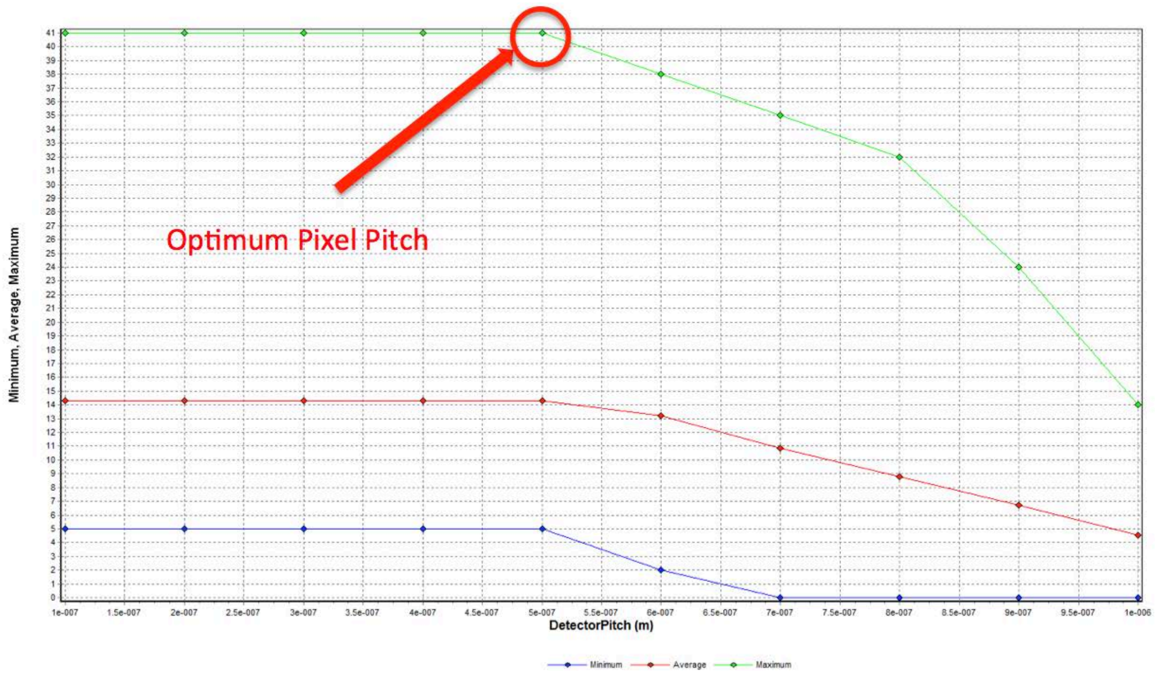

Figure 46. Optimal Pixel Pitch Plot

As one can see from Figure 46, pixel pitch has a maximum threshold value, which if exceeded will result in degrade coverage capabilities. In this case, the value at which degradation begins to occur is at $5 * 10^{-7}$m.

Another way to look at the data is presented in Figure 47, which shows the data charted onto a bar graph. For the sake of keeping simulation times down, only ten intervals were run. This has an effect on precision, as seen by the value of $4.1 * 10^{-7}$m in Figure 47 instead of $5 * 10^{-7}$m that is seen in Figure 46. For the sake of this thesis, the results from Figure 46 will be used; making the optimal pixel pitch to $5 * 10^{-7}$m.

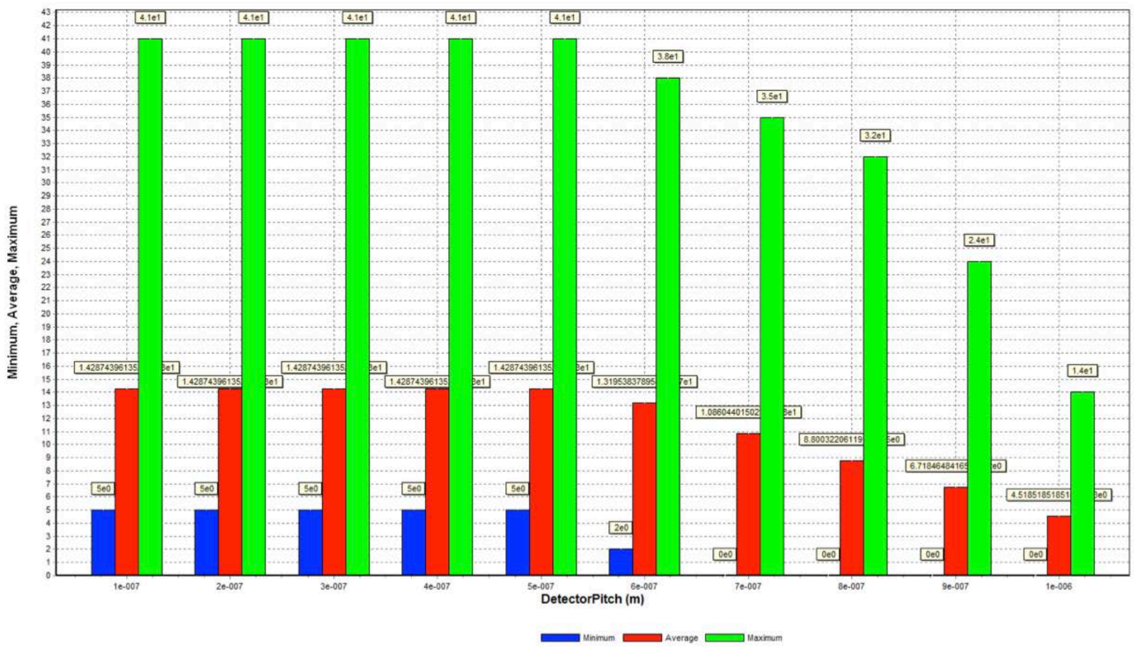

Figure 47. Bar Graph for Optimal Pixel Pitch

The next step in the study is to investigate optimal focal length. Again, the parametric study tool is employed as shown in Figure 48.

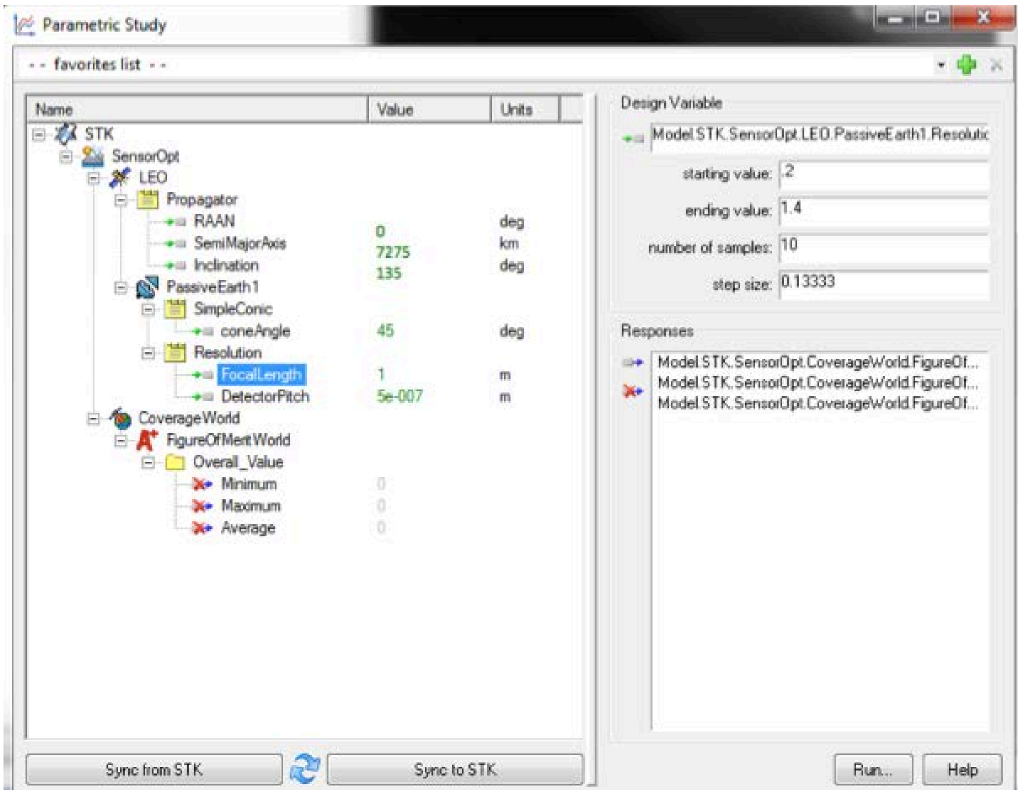

Figure 48. Parametric Study Menu for Optimal Focal Length

The design variables for Optimal Focal Length are given a starting value of 0.2 and ending value of 1.4.

Once the Design Variables for focal length are configured and the scenario run, it can be seen that focal length, just like pixel pitch, has a threshold value that when reached, does not improve coverage capabilities. The output of the scenario is shown Figure 49.

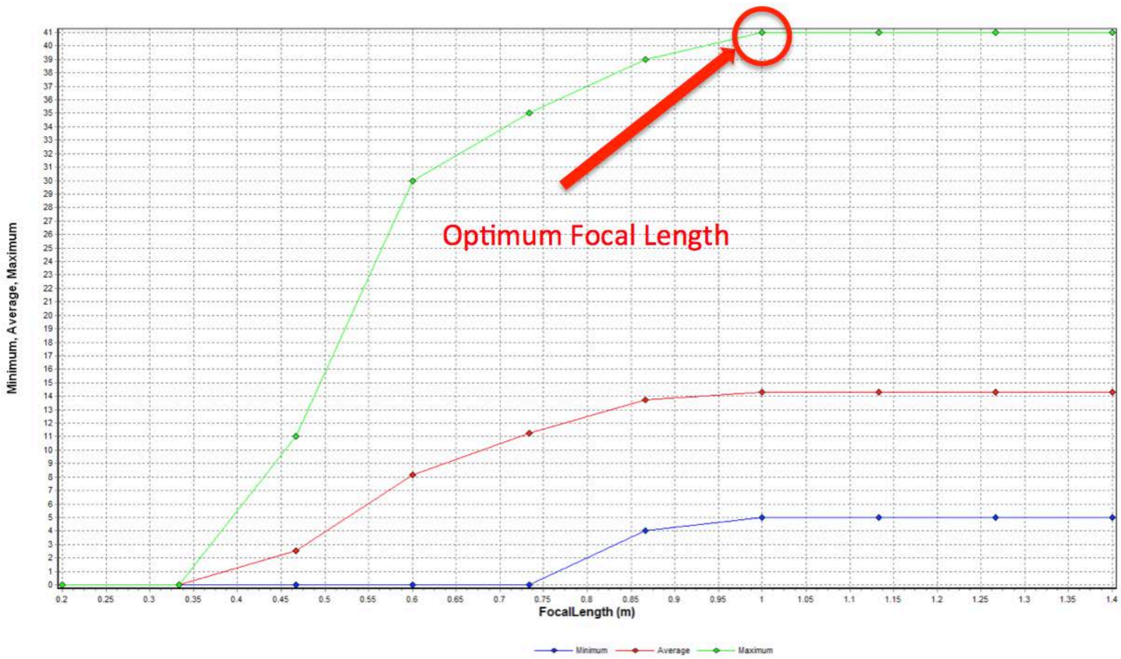

Figure 49. Optimal Focal Length Plot

The next step in the study was to run the two previous variables against each other and generate a carpet plot for focal length vs. pixel pitch. This was done to once again ensure that one variable does not affect the other. The results are shown in Figure 50.

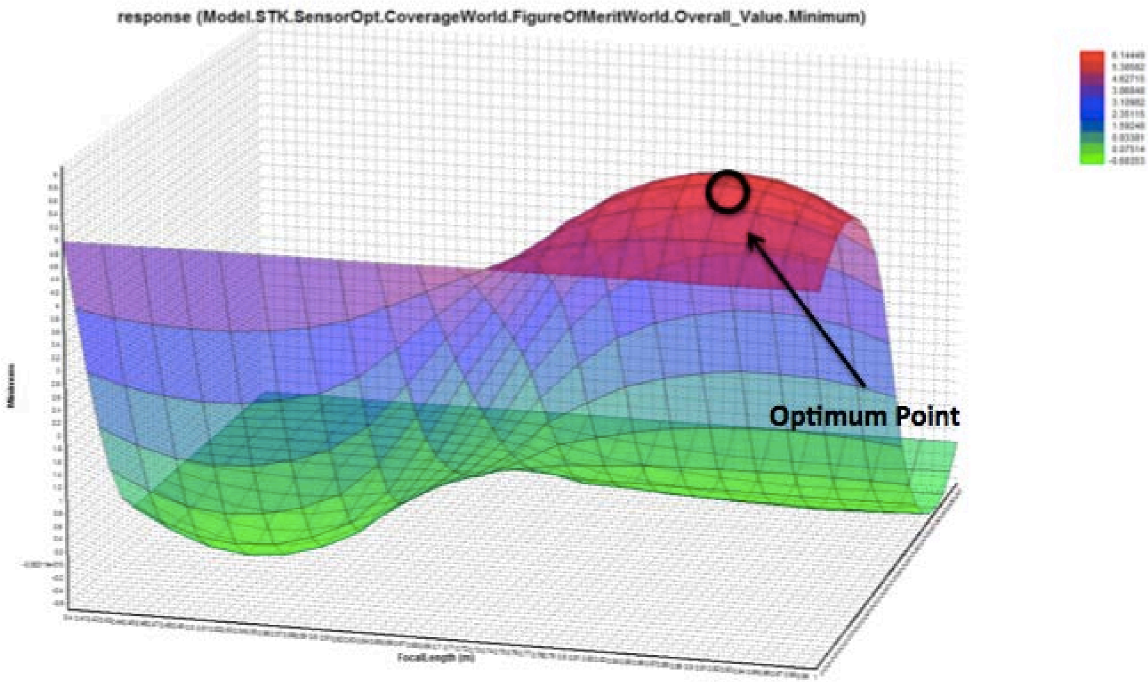

Figure 50. 3-Dimensional Plot of 2-Dimensional Parametric Study for Pixel Pitch vs. Focal Length

The carpet plot shows there is significant interaction between pixel pitch and focal length. The plot shows the focal length on the X-axis, number of revisits on the Y-axis and pixel pitch on the Z-axis. Again, the plot may be difficult to visualize if not viewing on in an electronic format, so a contour plot was also created. This is shown in Figure 51.

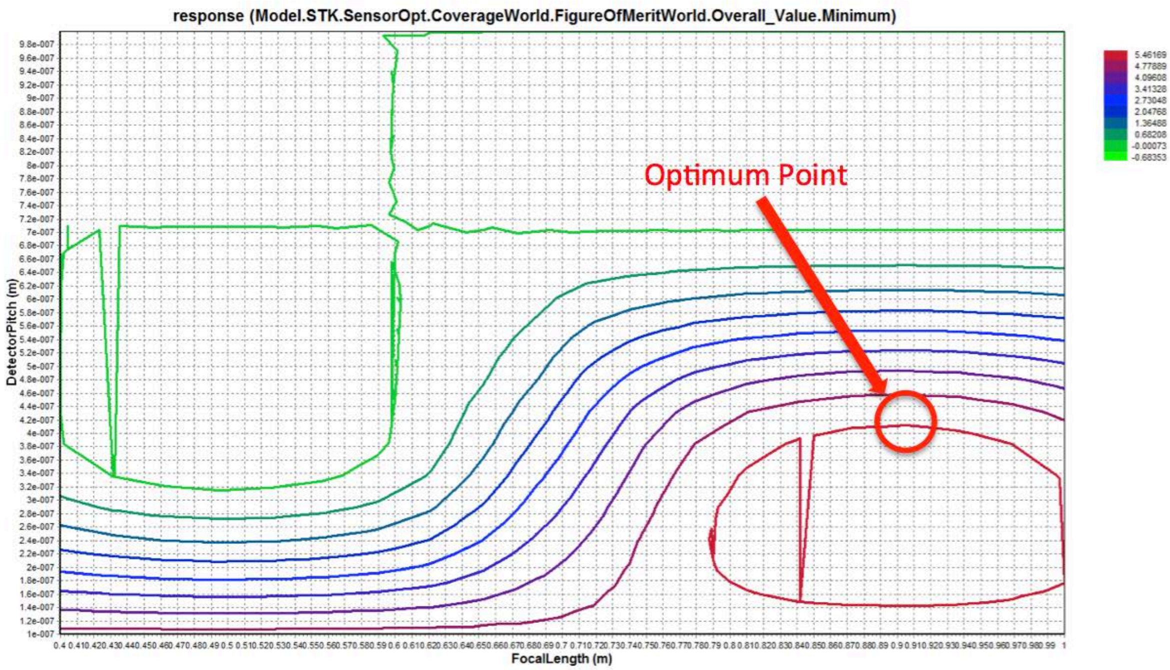

Figure 51. Contour Plot for Focal Length vs. Pixel Pitch

By looking at Figure 51, it can be seen that the optimal value for the two variables when interacting shifts a little from the values derived earlier. The Optimal point is shown in the lower right quadrant, with focal length around 0.9 and pixel pitch at $4.2 * 10^{-7}$m.

As can be seen by the previous simulations, finding the optimal parameters to design the nadir portion of the SSA system takes some concentrated analysis. Since the values found are not consistent, they can be further refined using the Sequence Optimization Tool (SEQOPT), also known as the Design Explorer Surrogate Optimization Tool.

SEQOPT is used to intelligently optimize surrogate models to accelerate the optimization process. However, in order to use SEQOPT, starting points are required, so the previously derived values will be used. The SEQOPT algorithm will be used to systematically modify variables in a Scenario until some objective is met. In this case, the objective was optimizing pixel pitch and focal length while holding semi-major axis and inclination at a fixed position. The setup of this tool can be seen in Figure 52.

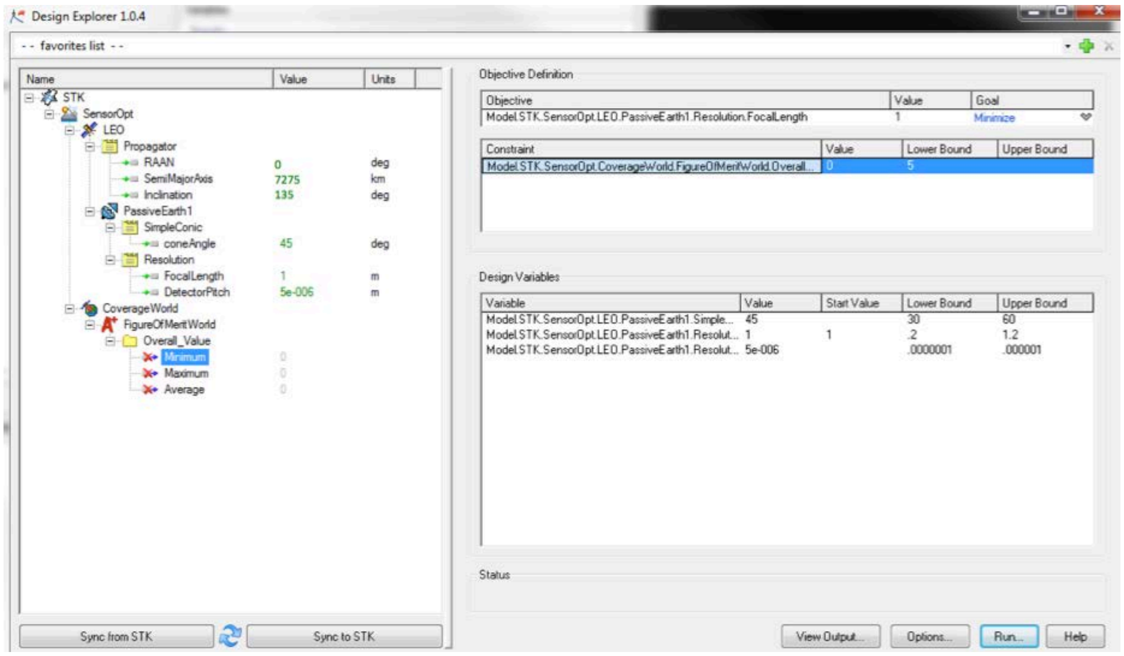

Figure 52. Setup of Design Explorer Surrogate Optimization Tool

Once the scenario is run, the output from the SEQOPT tool determined the following optimal values for the listed parameters.

- Focal Length: $2.0 * 10^{-1}$m
- Detector Pitch: $1.018 * 10^{-7}$m
- Cone Angle: 49.28^{0}

The output for these results can be seen in Figure 53 and Figure 54. Figure 53 shows the focal length vs. run number and Figure 54 shows the final report. For the purposes of this thesis, the values given above will be the final values used to design the nadir sensor.

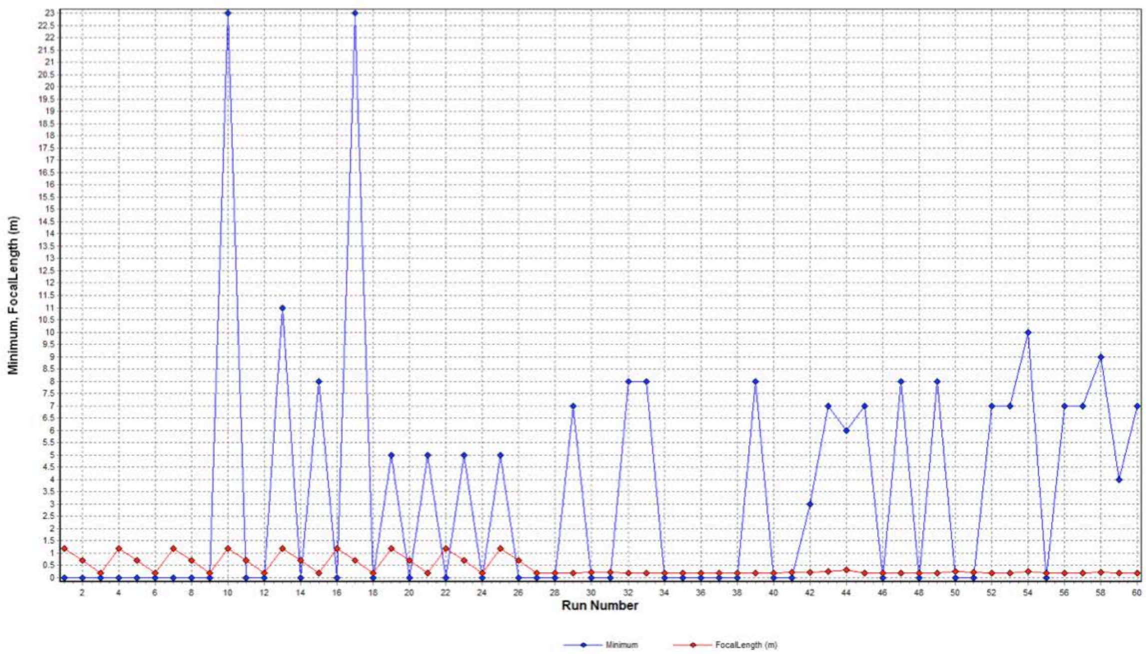

Figure 53. SEQOPT Tool Output 1

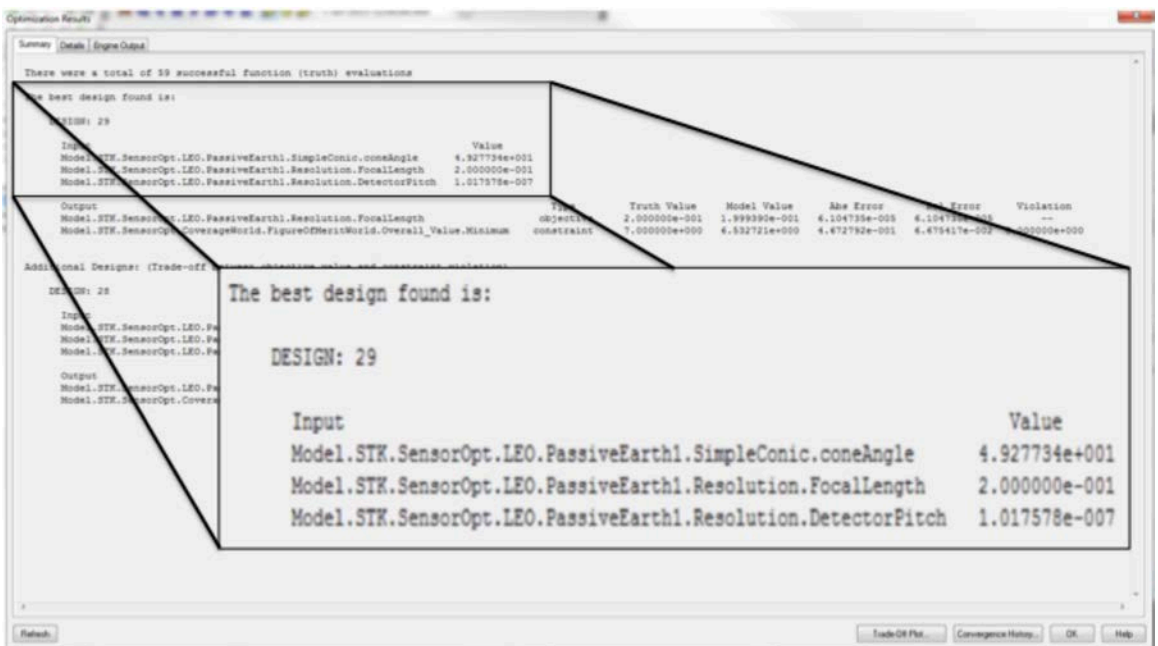

Figure 54. SEQOPT Tool Output 2

Now that the nadir sensor parameters have been specified, the next step is to determine the optimal parameters for the forward and aft facing sensors. To do this, the Electro-optical and Infrared (EOIR) toolkit will be used to analyze the SSA functions of

the sensors. Specifically, the EOIR will be used to determine what the signal-to-noise ratio (SNR) should be for the notional 1m sized targets. The SNR dictates how the sensor discriminates a desired signal, in this case the target, from the background noise, in this case other objects in space (e.g., stars, planets) (Wertz and Larson 1991, 243). Once this portion of the analysis is completed, the number of satellites to provide SSA in an entire plane can be derived.

The first step for this portion is to create two sensors on the spacecraft using the toolkit. The toolkit allows the properties of the sensors to be defined, as shown in the next several figures. The first step is to select the EOIR Sensor Plug-in as shown in Figure 55.

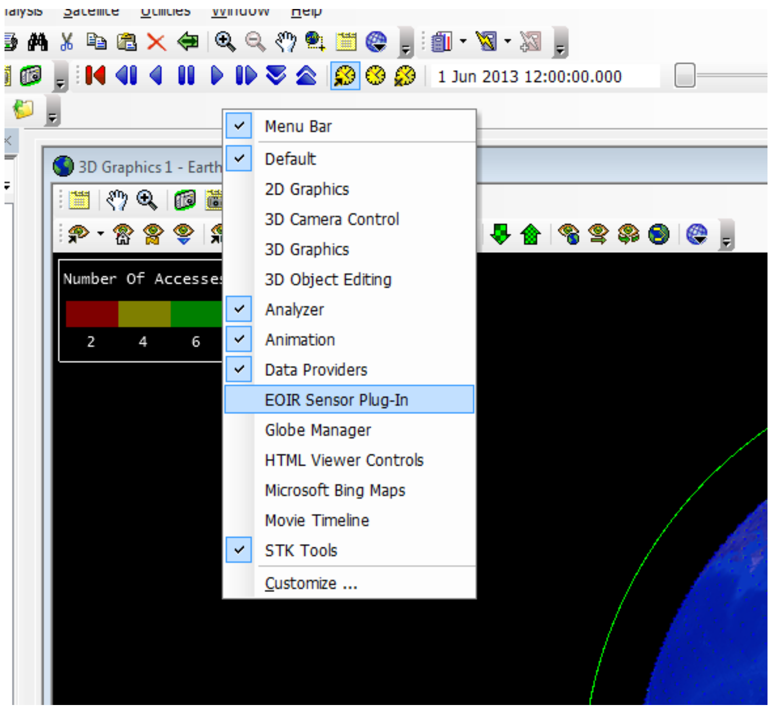

Figure 55. Select EOIR Sensor Plug-In

Once the EOIR Sensor Plug-in is launched, the properties of the sensor can be populated. In the Spatial tab for the sensors, a 10^0 Horizontal by 10^0 Vertical field of view was chosen as a notional sensor field of view. This is shown in Figure 56. The remaining values in the properties were default values used from STK and are shown in Figure 57 through Figure 59.

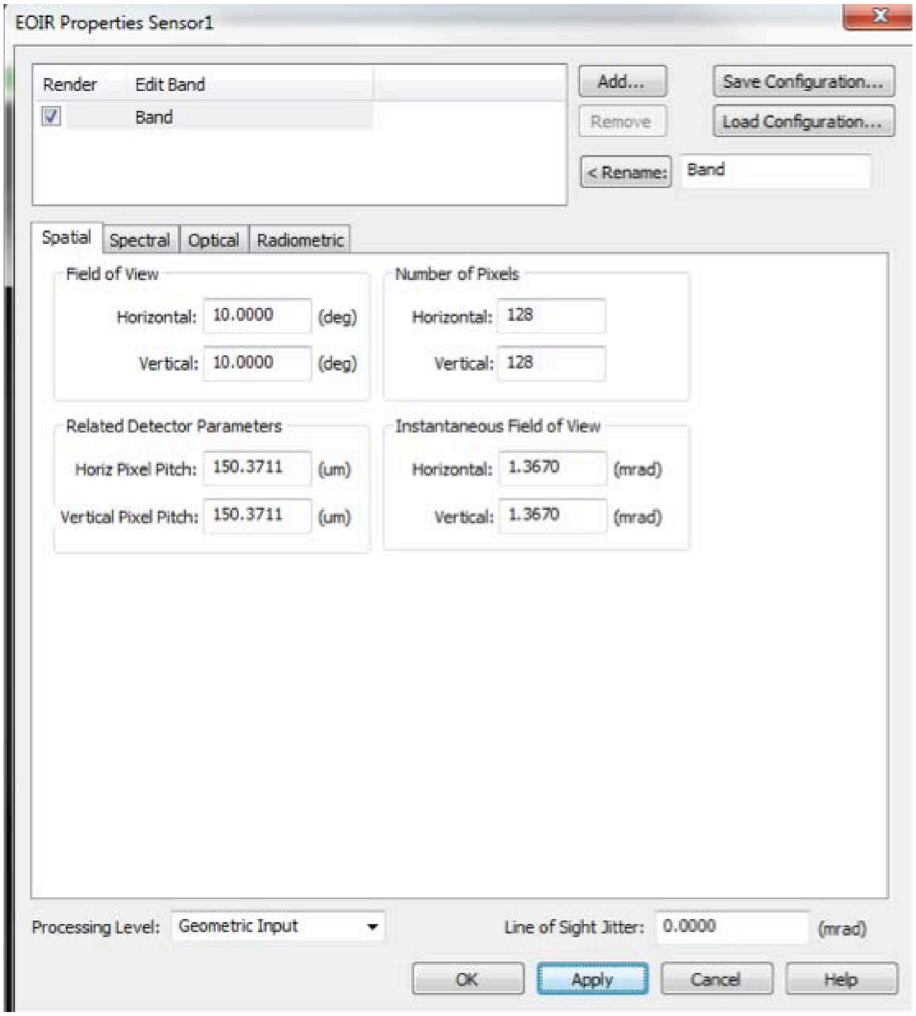

Figure 56. Sensor Properties # 1

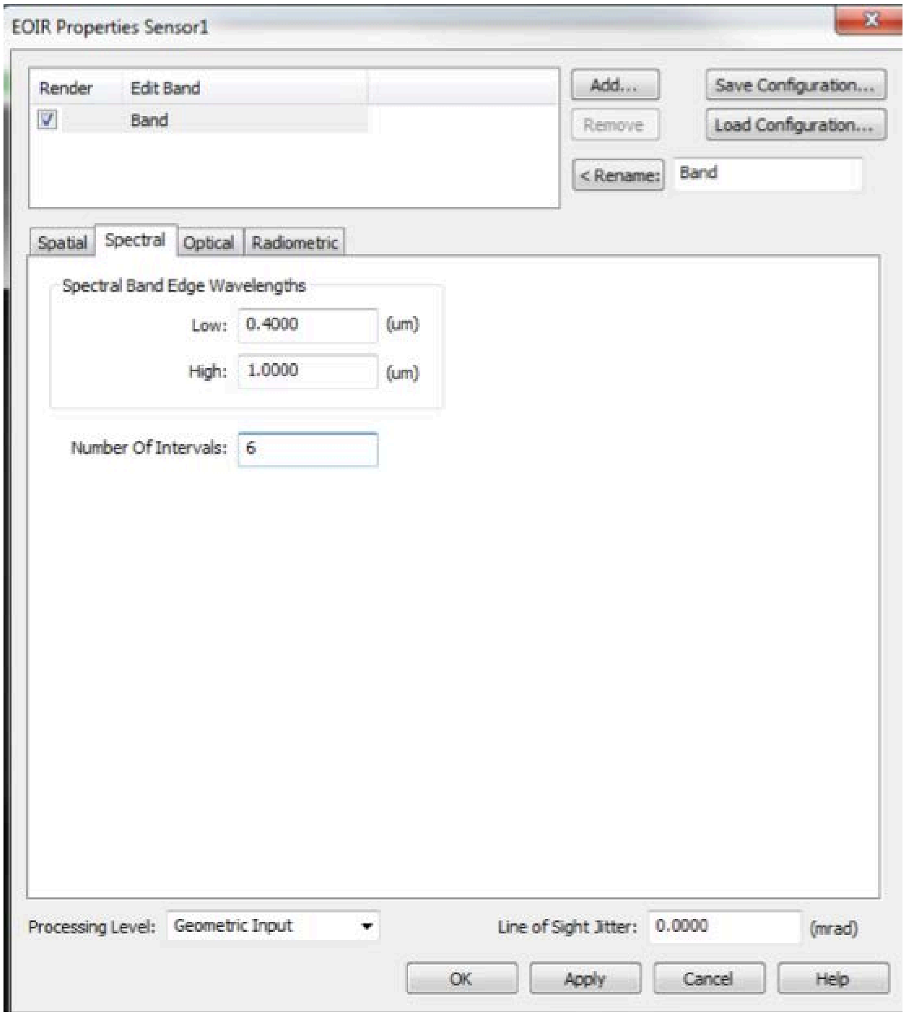

Figure 57. Sensor Properties # 2

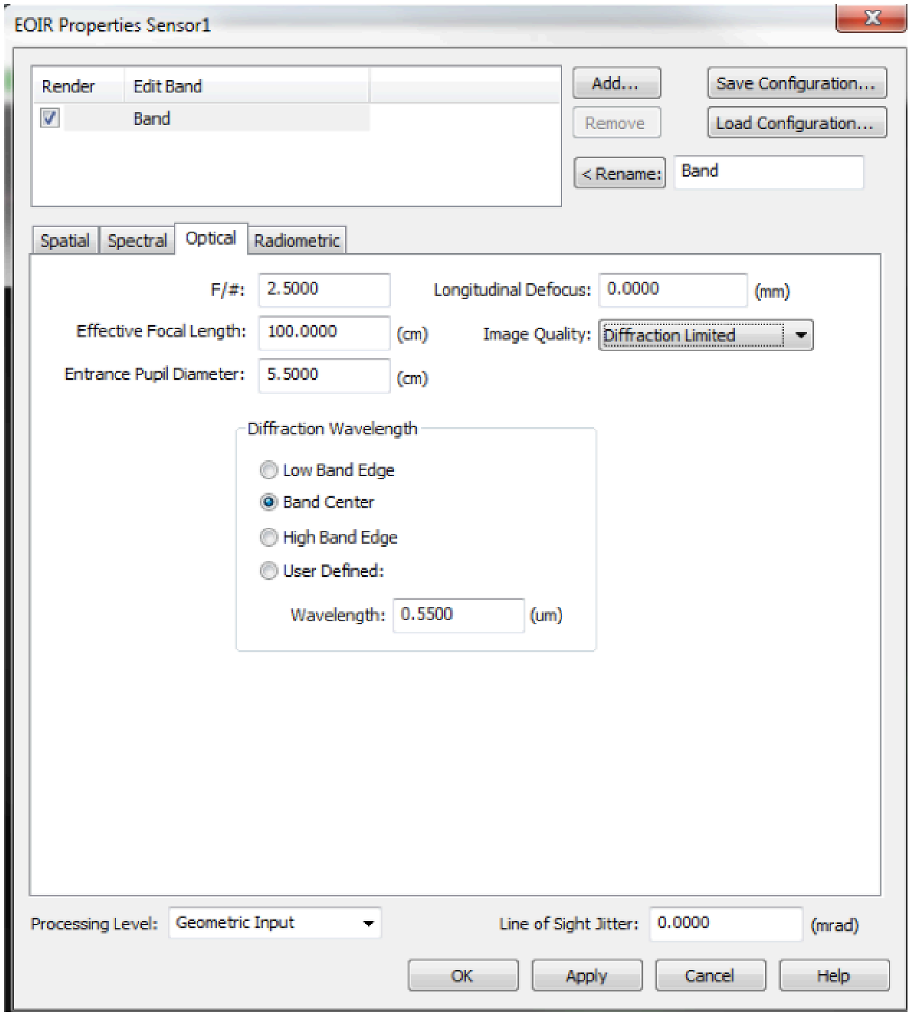

Figure 58. Sensor Properties # 3

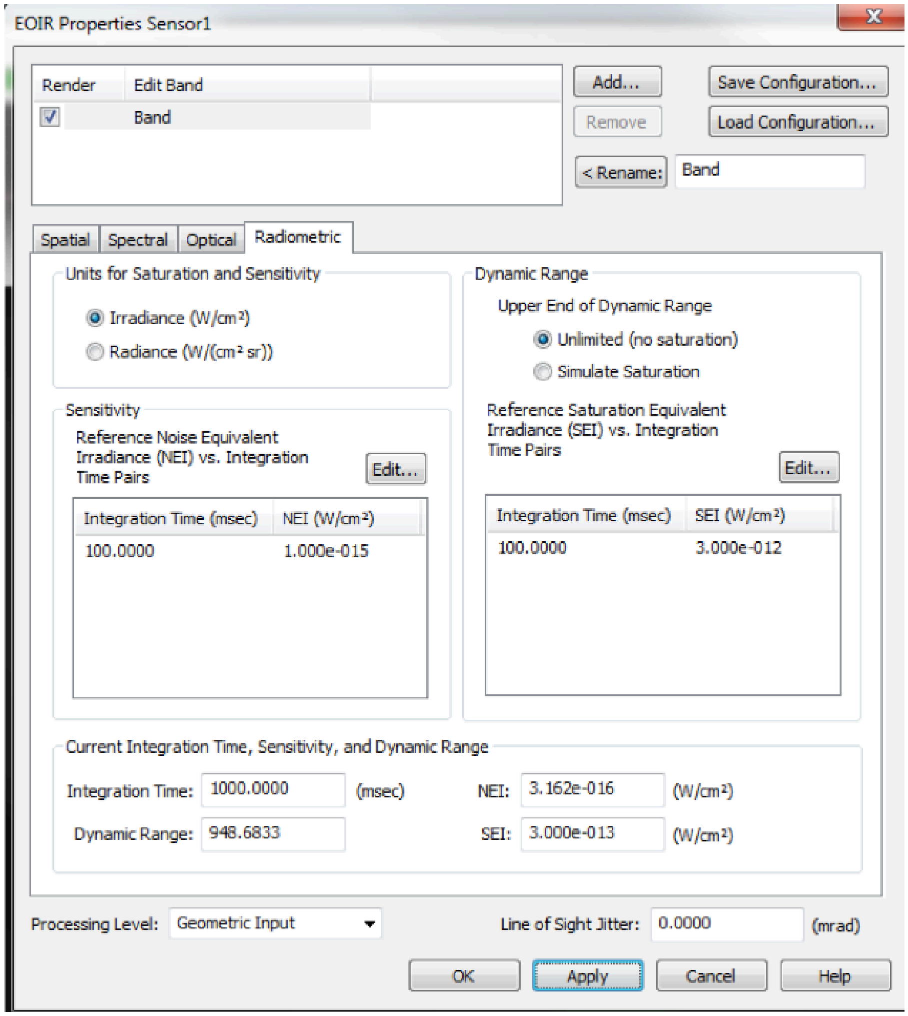

Figure 59. Sensor Properties # 4

Once the sensor properties are filled in, the Ok button can be pressed and the sensors are created.

The created sensors fields of view are shown in Figure 60 as the two bluish cones along the orbital path.

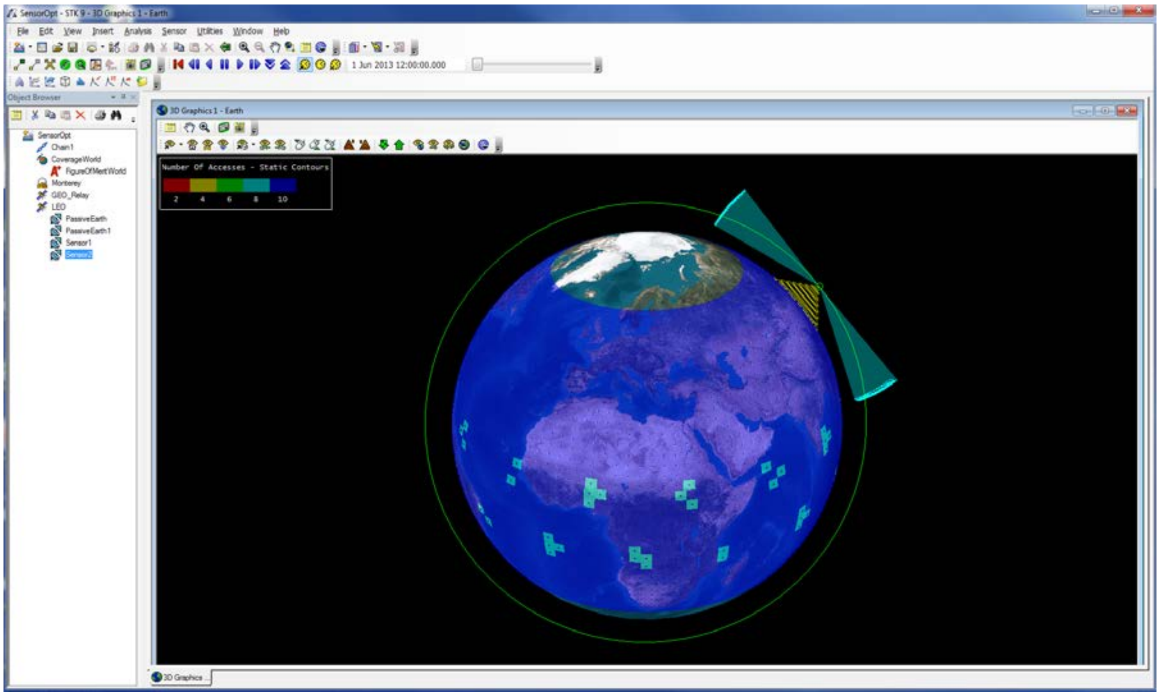

Figure 60. Forward and Aft SSA Sensors

After the sensors have been created, the next step is to create a target for the sensors to find. In this case, a 1-meter lambertian sphere (i.e., a sphere that is uniformly specularly diffuse or reflects light evenly) is created. In addition, 20% reflectance is specified for the target and grey body material is selected as a representative piece of space debris. Finally, the temperature of the object is specified as 273 Kelvin, or 0^0Celsius. This target is a notional piece of space debris since it would be near impossible to simulate every type of debris that could be encountered by an SSA sensor. However, the object should provide a sufficient simulation to develop parameters for the sensor. The setup for the target is shown in Figure 61.

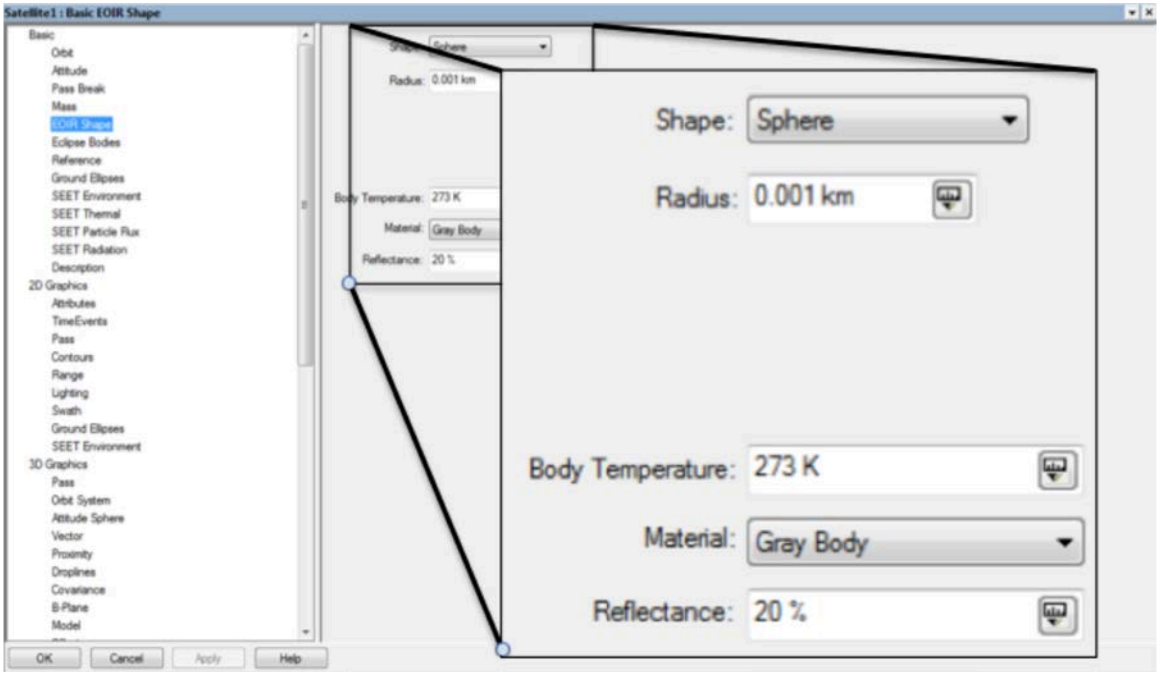

Figure 61. Debris Parameter Set-up in EOIR Toolkit

After the debris parameters have been specified, the orbit for the debris must also be specified. In this case, two objects are placed in the same orbital plane as our notional LEO hosted SSA payload 30^0 away in each direction. A visual representation of the debris in the orbital path is shown in Figure 62. They are labeled EO1 and EO2 in green lettering.

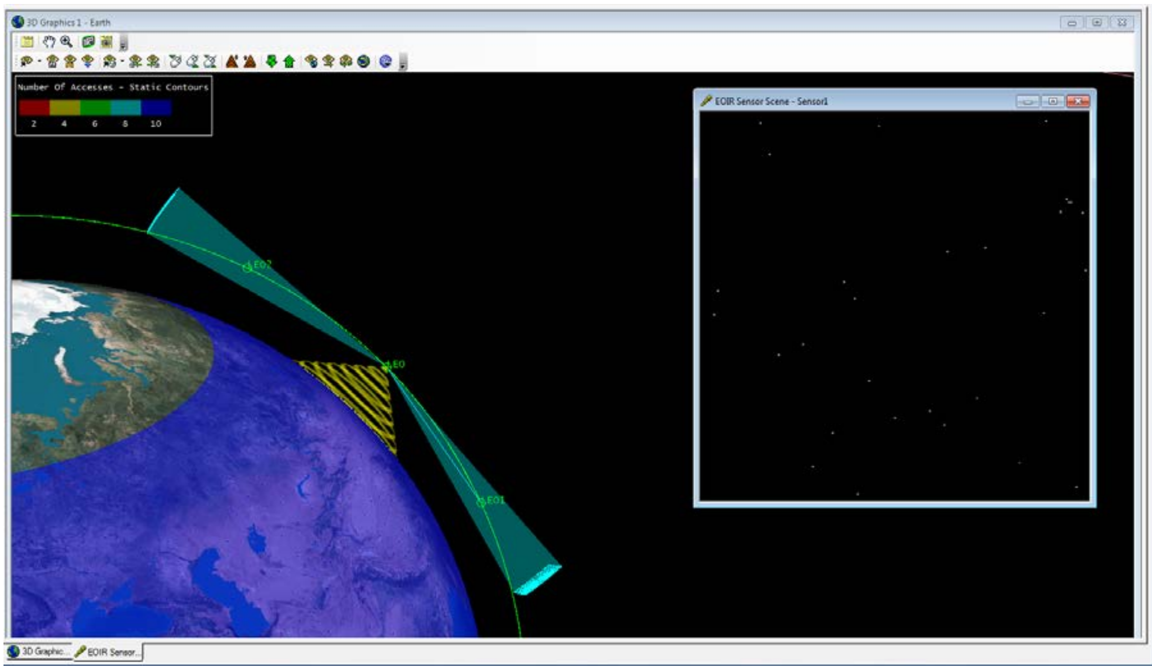

Figure 62. Space Debris in Orbital Plane

In the window to the right of the Earth in Figure 62 is a view of what the SSA sensor sees. To the casual and expert observer, it looks like a field of stars; however, one of the miniscule white dots in the field is actually the piece of debris created. While looking at the field of view does not allow debris to be differentiated from the stars, looking at the SNR does. The sensor, as it's orbiting, will compare the SNR of each of the objects to see what changes. If the object is a star, then the SNR will remain constant since the star is far away. However, if the speck in the field of view is a piece of debris, the SNR theoretically should change as the object gets closer or further away from the sensor. The objective and threshold values for SNR are not defined since a TRD was not

developed, so for the purposes of this simulation, a notional SNR greater than 2.0 will be considered sufficient.

To show how a piece of space debris or an object looks as it is moving through the sensor's view, the following three figures are provided with the debris circled in red in each one. The reader should take notice of the cluster of two stars in the yellow square and how they move in relation to the debris.

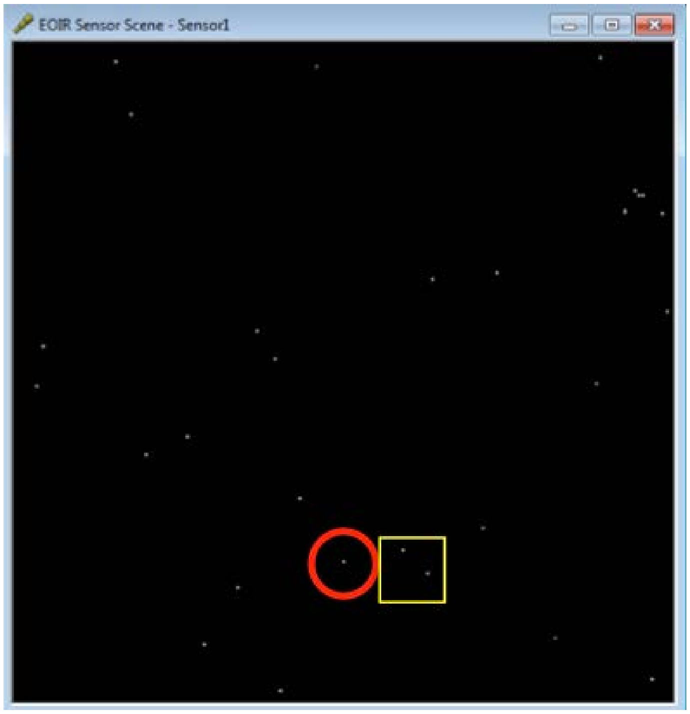

Figure 63. Sensor Debris and Star View # 1

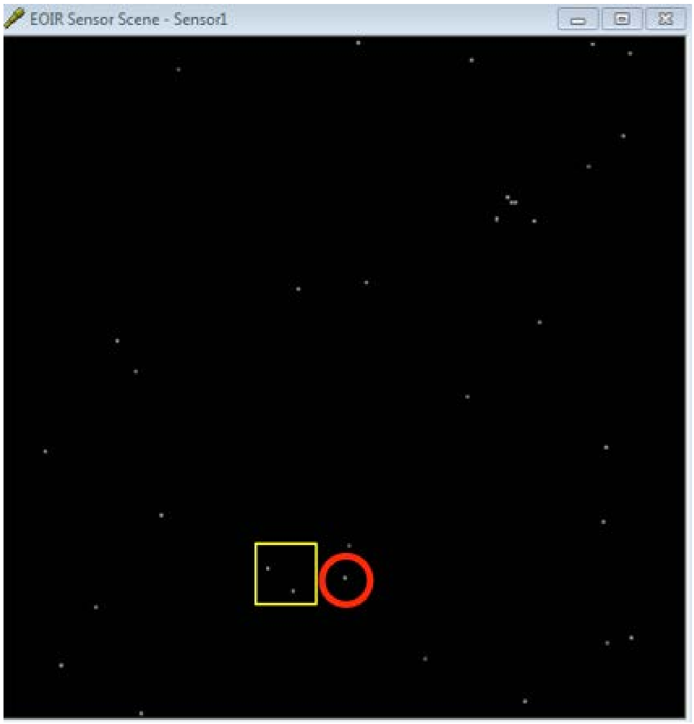

Figure 64. Sensor Debris and Star View # 2

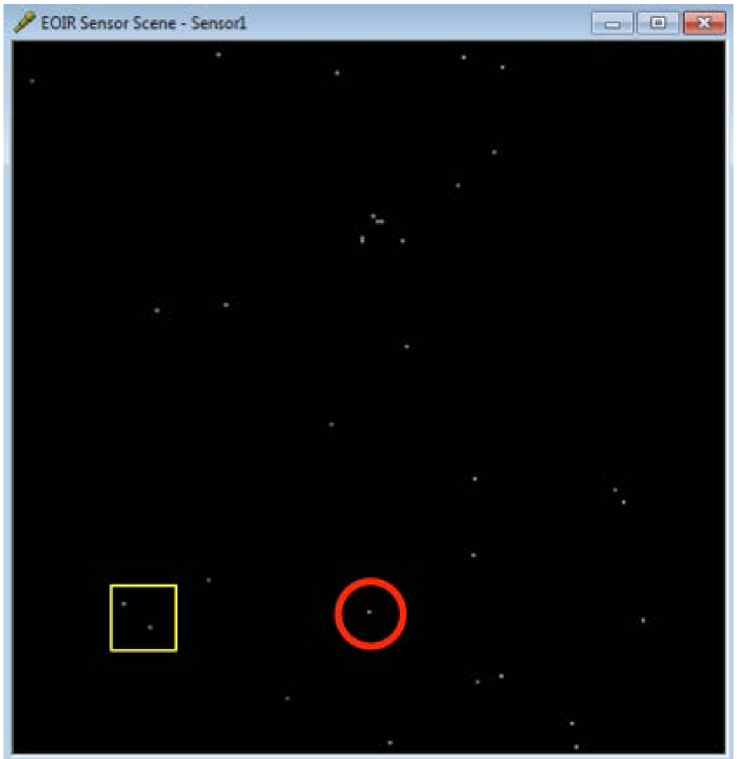

Figure 65. Sensor Debris and Star View # 3

Now that the reader understands how the object appears to the sensor, the next step was to run the simulation to discover what the SNR is for the objects 30^0 away. This is accomplished by generating the sensor-to-target metric report in the EOIR toolkit as shown in Figure 66.

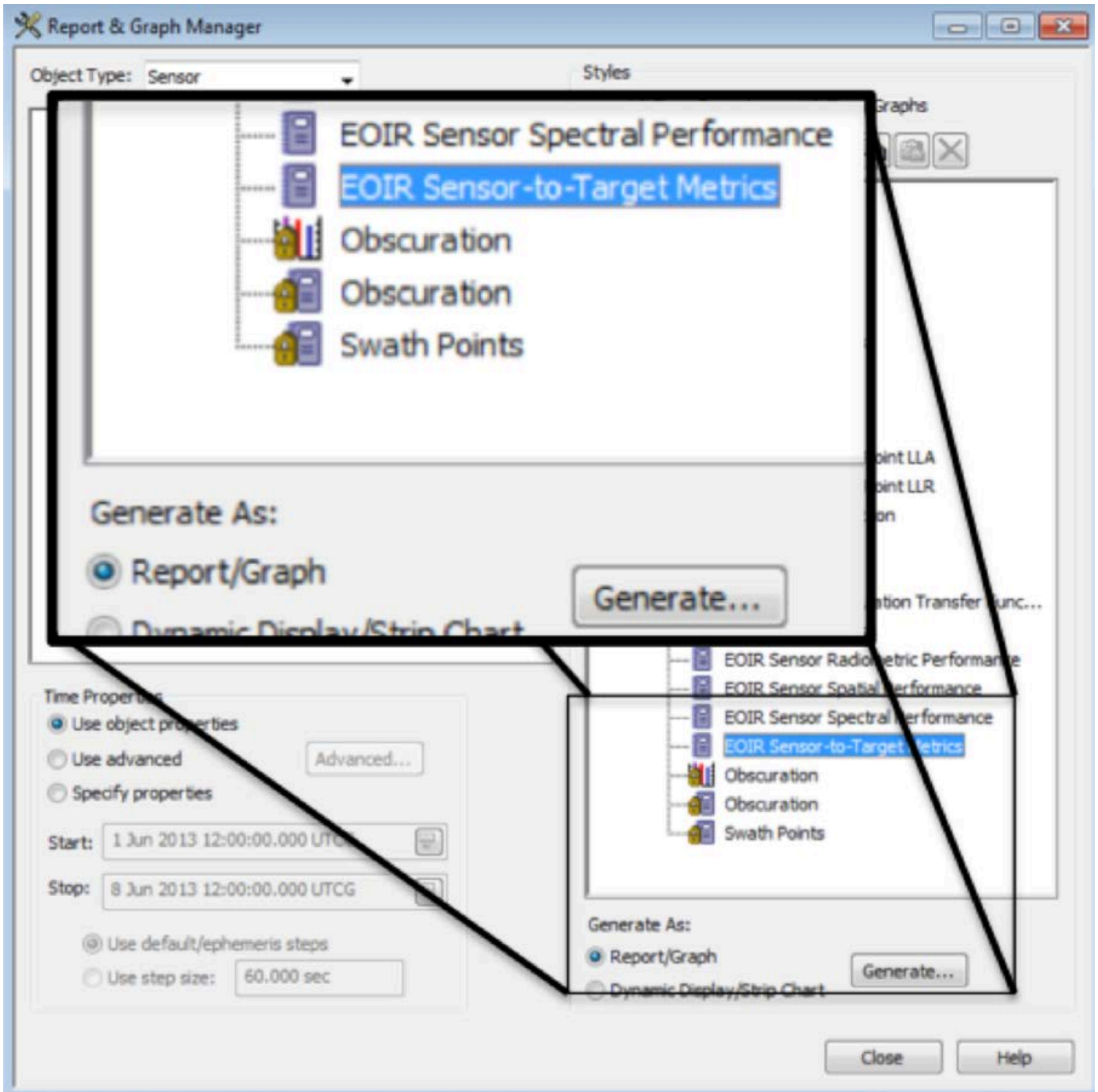

Figure 66. EOIR Sensor-to-Target Metric Report Generation

Once the Generate option is selected, STK steps through a 60-minute simulation to show the changing SNR of the space debris in the orbital path. The results are shown in Figure 67.

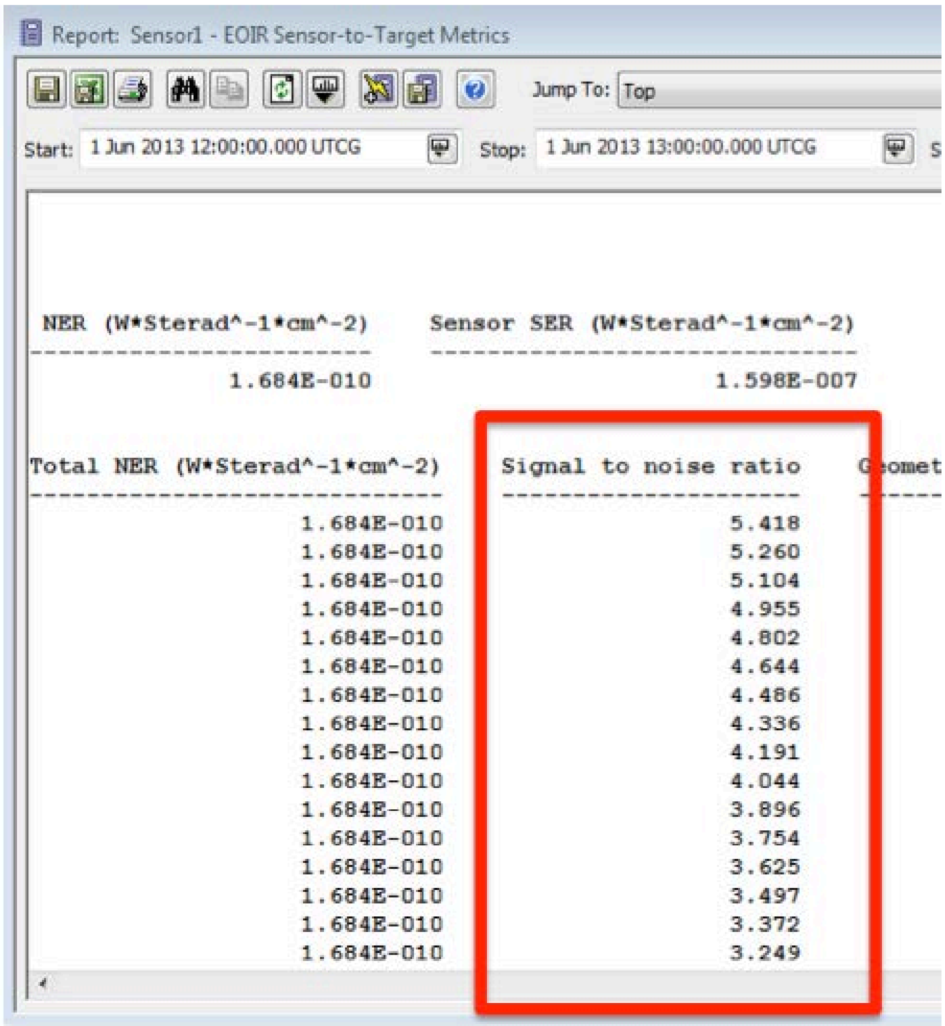

Figure 67. SNR for Space Debris 30^0 Away

As can be seen from the report, the SNR is around 5.4 at the point the object is closest to the sensor. As the object drifts further away from the sensor, the SNR decreases to around 3.2. For the purposes of this thesis, this means the SNR has exceeded the goal of 2.0, and the sensor parameters can be considered sufficient for use as hosted SSA sensors.

Now that the optimal orbit and sensor parameters for the nadir, forward and aft sensors have been determined, the final step is to replicate the single satellite multiple times to provide coverage for an entire orbital plane. This is done using a simple copy and paste function in STK to replicate the LEO satellite and spacing them evenly around the globe. The results can be seen in Figure 68 and Figure 69.

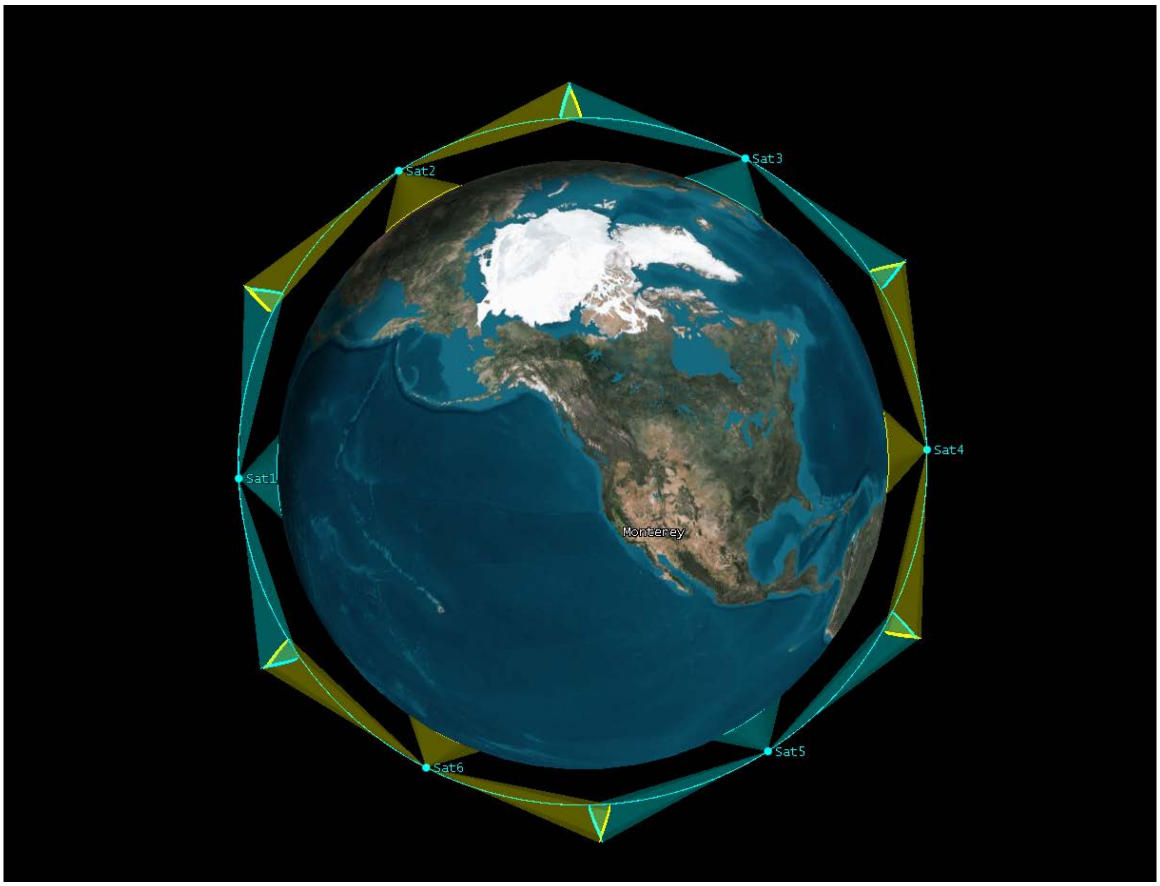

Figure 68. Single Plane Hosted SSA Payload Constellation

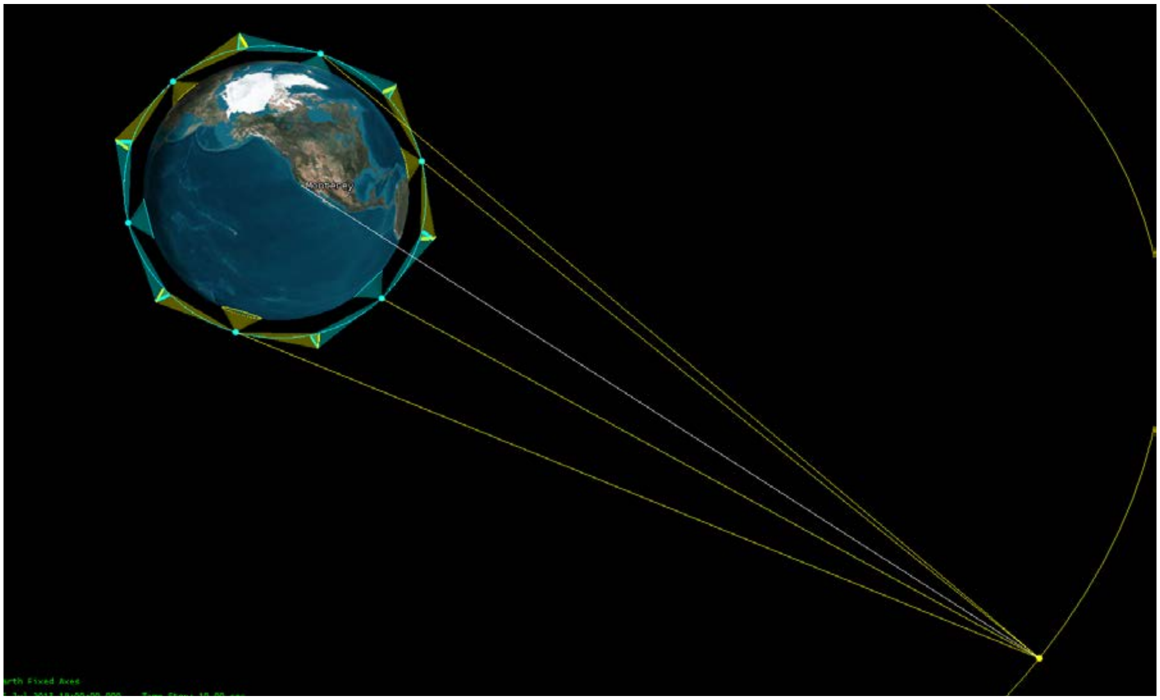

Figure 69. Single Plane Hosted SSA Payload Constellation with GEO Relay and Downlink to Monterey, CA

What can be seen from the final images is that six satellites are required to provide worldwide SSA using hosted payloads in a single plane. It should be noted that this constellation has been optimized to provide maximum coverage of the Earth from the nadir facing sensors as well.

C. ARCHITECTURE CONCLUSIONS

After the requirements and the simulations were completed, the final step for developing the architecture was to develop an Operational View (OV) for the proposed system. An OV is one of the basic views in the Department of Defense Architecture Framework (DoDAF). The OV-1 is the high-level graphical and textual description of the operational concept. This View will provide a means to visualize and understand the broad scope and complexities of the architecture being proposed. In particular, the Operational View will detail the complex operating domain in which the final system will operate (DoD Deputy Chief Information Officer 2011, 139). Figure 70 shows the proposed OV-1.

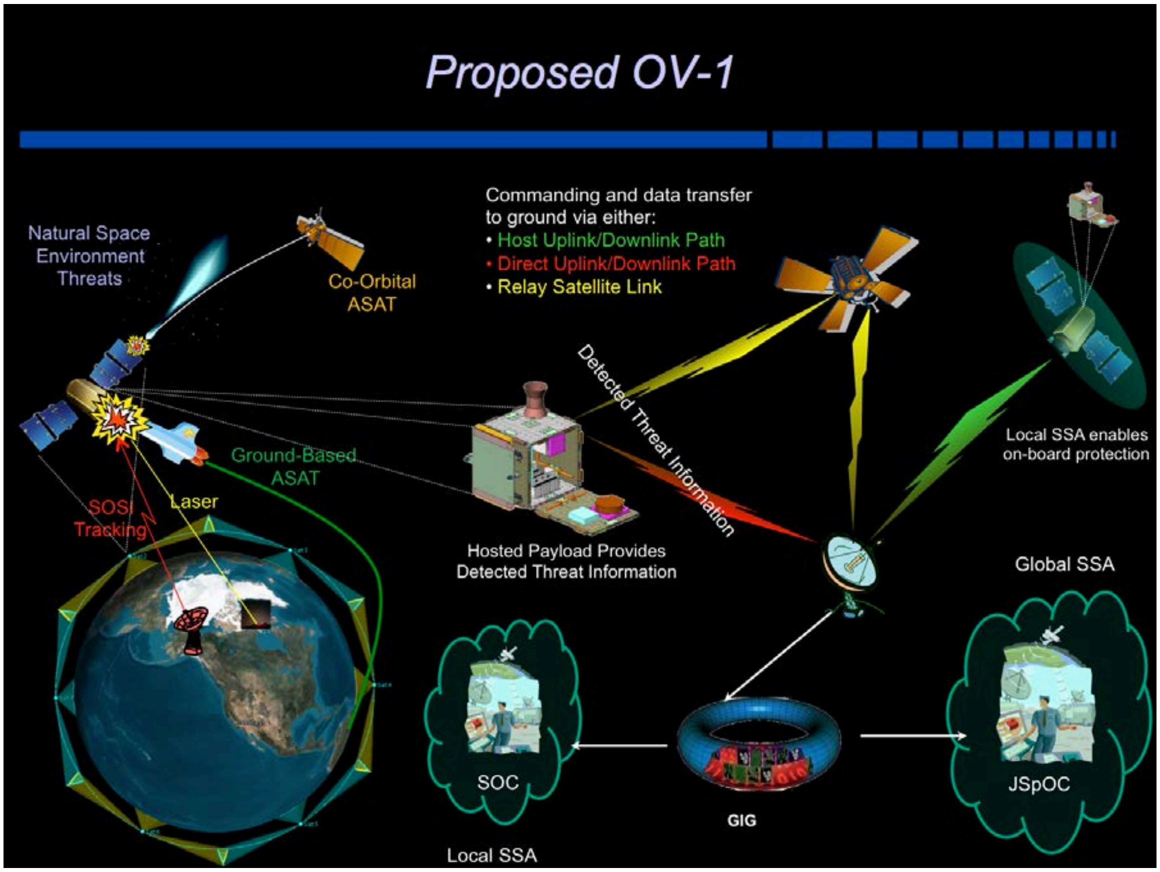

Figure 70. Proposed Operational View

To better understand the OV, the OV should be looked at from left to right. In the bottom left corner, the proposed constellation from the STK simulations is shown orbiting the Earth. On the Earth are several threats, SOSI tracking stations, laser threats and ground based anti-satellite weapons. A single satellite from the constellation is portrayed in more detail encountering several threats. The three ground-based threats described earlier as well as natural environmental threats, such as meteorites, and co-orbital anti-satellite weapons are also introduced. From this single satellite, a representative hosted payload is shown relaying threat information from the sensors over varying communication methods. The communication methods shown include a relay satellite, shown as a connection with yellow lines, as well as direct communication from the payload to the ground, shown by the red line. Additionally, another hosted SSA system on a satellite is shown in the upper right hand corner. This system depicts information being sent over the host spacecraft communication link. Finally, once the

data has arrived to the ground station, represented by the satellite dish receiving the communication signals, the data can be passed over the global information grid (GIG) to the JSpOC or space operations center (SOC).

The information passed to the SOC is what was called “local” SSA at the beginning of this thesis. The local SSA would be provided to the user of the particular satellite and could be used to better understand what is happing to the particular spacecraft. In addition, by utilizing the information form the hosted payloads and sending the information into the JSpOC, the data can be fused together to begin providing “global” SSA.

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V. CONCLUSIONS

A. RESEARCH SUMMARY

Currently the U.S. relies on primarily on ground-based radars and one space based system to provide SSA. However, there are other means to provide SSA the U.S. should use. Satellites are launched on a regular basis for defense, scientific and commercial purposes. These satellites all hold the potential to contribute to the worldwide SSA picture by utilizing hosted SSA payloads on board. These unconventional payloads provide the flexibility in cost and performance that cannot be achieved by conventional SSA systems. In addition, hosted payloads paired with the correct instruments provide a capability that does not currently exist with ground-based radars. This capability is "local" SSA, a means for a satellite and its operator to know what is in a spacecraft's immediate vicinity. Additionally, if the data from hosted payloads is properly fused and analyzed, the capability to develop a worldwide SSA picture (i.e. "global" SSA) exists.

To understand what would be required to develop a SSA architecture utilizing hosted payloads, two research questions were asked:

1) What are the requirements for an individual satellite to provide local SSA using a hosted payload?

2) How should individual SSA payloads be distributed to provide a worldwide SSA picture? In other words, what should the architecture look like?

By examining these two questions, this researcher set out to understand how to provide SSA using hosted payloads.

To answer the first question, multiple programs were studied to gain a better understanding on what type of requirements would make for a successful hosted SSA payload. Ultimately, nine generic high-level requirements were developed to build a hosted SSA payload. These nine requirements were the answer to the first question. These requirements provide a means to develop the underpinnings of a SSA architecture based on hosted payloads. Having a hosted SSA payload that is adaptable to multiple

scenarios and can accommodate various sensors is the best means for providing SSA via hosted payloads on multiple satellites.

The second research question in this thesis was answered by performing physics based analysis using STK. The purpose of the analysis was to design a notional system in a single plane that maximized SSA using the hosted payloads. Due to the academic nature of the analysis, the analysis was bounded to a single plane. The optimal orbit was found which would maximize SSA, and three notional sensors were designed to support "local" SSA. At the conclusion of the STK simulations, it was found that six satellites with hosted SSA payloads could provide a worldwide SSA picture in a single plane.

Using the requirements and the STK simulations as a basis, an OV-1 was developed as the final architecture product for this thesis. The OV-1 provides a notional depiction of the architecture for "local" and "global" SSA. By fielding the hosted SSA payloads around an orbital plane and distributing the threat data to satellite operations centers as well as the Joint Space Operations Center, "local" and "global" SSA can be achieved.

B. AREAS FOR FURTHER RESEARCH

Since this thesis was limited in depth and breadth due to the academic nature of the work, there are areas for further research. The requirements analysis was limited to high-level requirements since information required to develop a TRD was not available in the academic setting. One area for additional work is to develop a TRD, which further defines the hosted SSA payload requirements. Additionally, some requirements may require technology that is above the unclassified level. Any further requirements development should be done at the appropriate classification level to ensure appropriate security is maintained.

For this thesis, limited analysis was performed at a high level. If this system were actually to be built, further analysis, such as more detailed functional analysis, function to physical mapping and environmental analysis would need to be performed as well. Also a reliability analysis could also be conducted to determine how well the system would perform over time.

The analysis that was conducted with respect to sensor development was done with notional values. An area for further research would be to use realistic values from sensors developed by the defense industry and rerun the simulations. The analysis may reveal that additional satellites are required to provide worldwide coverage.

Another area for further research is with respect to the field of views of the sensors. The sensors modeled in this thesis only provided SSA in the nadir, forward and aft directions of the satellite. Further modeling could be done with a sensor that provides four-pi steradian coverage (i.e., a 360^0 sphere around the satellite).

Finally, the research conducted in this thesis was limited to a single plane to ensure computational times for simulations were kept to reasonable amounts. To truly develop a sense for how many satellites would be required to provide coverage in all orbital planes, further simulations should be conducted. In addition, the simulations conducted should be expended from LEO to MEO and GEO satellites as well.

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